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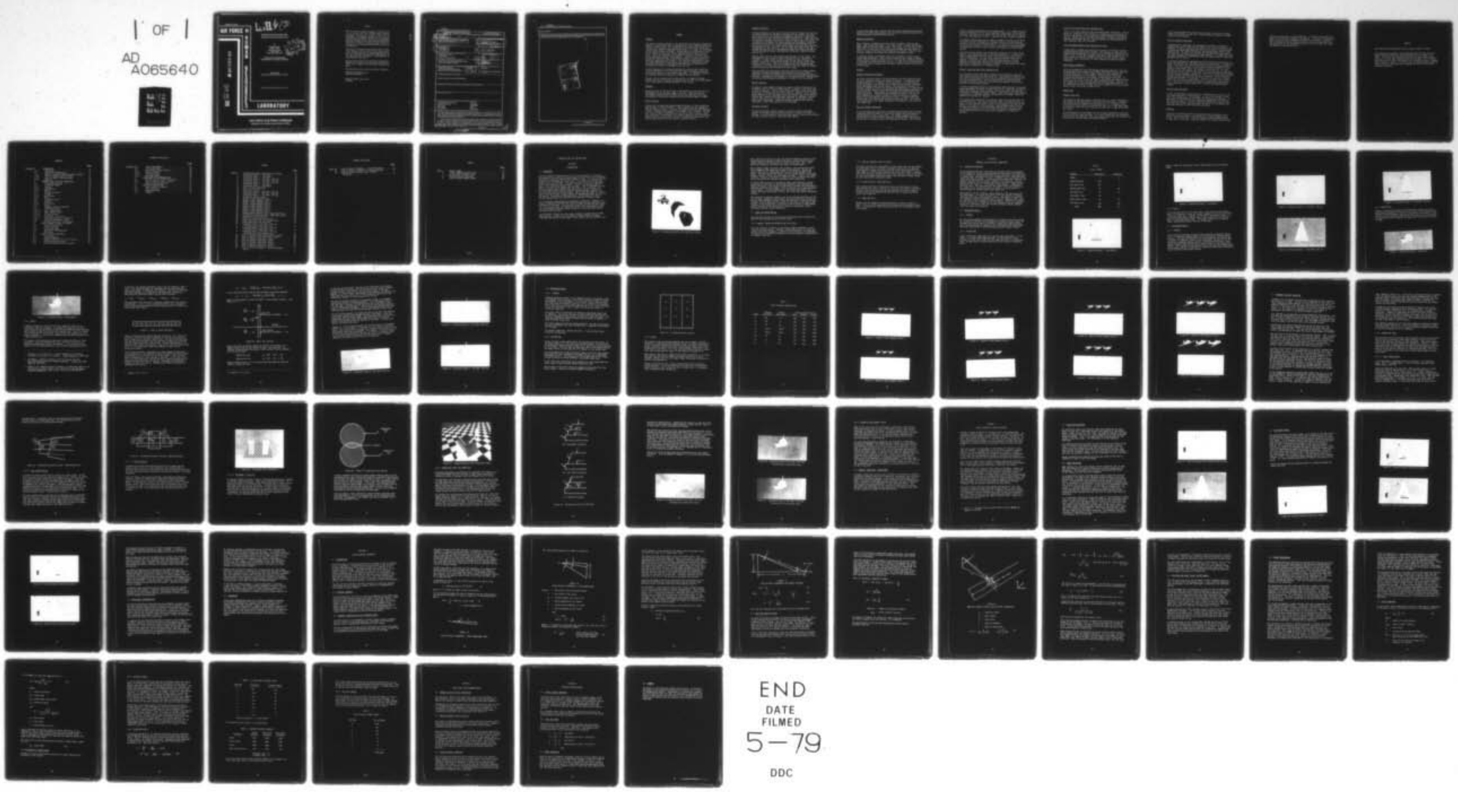

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HUMAN RESOURCES

LEVEL II

COMPUTER IMAGE GENERATION:
IMPROVED EDGE UTILIZATION STUDY

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LABORATORY

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Computer Image Generation (CIG) systems for visual scene simulation are now being procured for research and as pilot training simulators. Any given system has limited edge capacity, so it is important that the edges be utilized effectively to provide the simulated visual scene for training. The level-of-detail concept in current CIG systems improves efficiency of edge utilization.

A feature at such a distance that it has a small view window image is computed at a low level of detail using few edges. As the viewer approaches the feature, and its image becomes larger, a model containing more detail and more edges is computed to represent it. The high sensitivity of the eye to abrupt changes makes the transition distracting and limits the usefulness of this technique. This study developed techniques to produce a gradual

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transition from one detail to the other. Evaluation scenes and sequences demonstrated this to be far less obvious and distracting. Another area of investigation provided high detail in the portion of the view window to which the view is directed (the "area of interest") with gradual transition to low detail elsewhere.

SUMMARY

PROBLEM

The general problem attacked in this study was the imbalance between the amount of visual detail that is desirable for various aspects of mission training and that which can be provided by existing visual simulation systems using computer image generation (CIG). The "edge" is the primary unit of which scenes are formed. System capacity is expressed in terms of the number of edges that can be processed and displayed to form a scene. An obvious approach to the general problem is to design and build systems with greater edge capacity. Since the first CIG systems were built, there has been a continuing increase in edge capacity in successive generations of systems. The continuing development of more efficient algorithms and the use of more powerful integrated circuits have made increases in edge capacity possible without the burden of proportional increases in hardware size and cost.

A second approach to the general problem of providing more effective visual scene detail is to use primitives other than edges, where they can provide realism at less expense than edges. Ellipsoidal features and non-edge texturing schemes are examples of this approach.

Finally, given a system with a given capacity of edges (and other primitives), what can be done to improve the utilization of these edges? This is the specific problem addressed in this study.

APPROACH

Modeling refers to the definition of the features in the data base or environment, using vertices, edges, and faces. Modeling of each environment feature should be done so that the required visual cues and degree of realism are provided using the minimum number of edges.

LEVEL OF DETAIL

A major tool in achieving improved edge efficiency in past systems has been the use of level of detail. A given feature will be modeled to several levels of detail. A house, for example, may have such features as doors, windows, and chimney in its highest level of detail, with the next level of detail containing only the basic house structure. When the significance of the detail on a feature decreases due to distance or other criteria, a lower detail version is computed and displayed, thus freeing edge capacity for use on more important features.

Gradual Transition

The major objection to the use of level of detail has been the fact that the abrupt changes are extremely noticeable to the viewers, and draw their attention to the change with subsequent reduction of realism and interference with the task they are being trained to do. Some years back, the concept of gradual transition of level of detail was first tried. As a runway was approached, the runway markings were gradually introduced. The effect was a gradual, natural appearance of the markings with no distracting effects. The capability to handle such cases has since been incorporated in real-time CIG. The fact that the colors of the face (runway marking) and of its background (runway) are fixed and known at the time of modeling makes implementation relatively simple for cases such as this.

Gradual transition for three-dimensional features is less simple. The background for any portion of such a feature will be a function of viewpoint. Further, when transitioning from one level of detail to another, there will in general be changes in the outline of the image from one to the other. Not only do these facts pose implementation difficulties, but they raise the possibility that the effect of gradual transition might be unsatisfactory in these cases.

These problems were attacked by devising algorithms to produce dynamic sequences incorporating gradual transition and by applying these algorithms to scenes representative of those in which problems might be expected. Subsequently, an approach to a hardware-feasible implementation was devised and validated by applying it to some of the test scenes.

Area of Interest

In general, large numbers of edges are used to display features in the peripheral area of vision when more detail is needed in the target area or area of interest. Level of detail selection rules could be revised using area of interest as one of the criteria. However, if this caused abrupt changes as the view swept across the display, the effect would be distracting. Several algorithms were developed to implement a gradual spatial transition from a high-detail region of the display to the lower-detail background. Scenes and dynamic sequences were made for evaluation of the effectiveness of this technique.

Selection Criteria

In previous systems, several types of selection criteria have been applied to initiate transition from one level of detail of a model to another. In each approach, there have been cases of transitions occurring at times and places such as to detract from realism.

In this study these past criteria and the results achieved were analyzed, additional criteria were examined, and rules for transition selection to provide improved performance were devised.

Modeling Guidelines

When a feature is modeled at several levels of detail, there are two goals. One is edge efficiency -- the lower levels of detail should use fewer edges than do the higher levels. The second is to achieve graceful transiton -- to minimize visual differences between adjacent levels of detail. These are obviously conflicting goals; however, effective level of detail modeling can achieve satisfactory approaches to both.

In previous systems the modelers have had no guidance in ways to best achieve the second goal. While gradual transition will greatly improve visual effects during transition, it is still true that effective modeling is necessary to achieve the best results. A study of past practices and results was used to develop level-of-detail modeling ground rules as part of this study.

RESULTS

Gradual Transition Evaluation

The first evaluation scenes involved features for which adjacent levels of detail involved little or no change of outline. A runway with and without markings is an example of such transition. The results were fully satisfactory, as had been anticipated from the earlier time-lapse movie experiments with similar scenes. The evaluation of scenes involving a change of outline and including the appearance of a new portion of the structure against a non-uniform background produced completely unexpected results. The problems that had been anticipated were practically nonexistent. Where there was a moderate change in outline, the effect appeared as a spatial transition from one version to another. Where a tall mast appeared against the horizon, it required detailed examination to see the horizon bleeding through the mast. This effect can be explained by the mutual inhibition of receptors in the retina of the viewers eye.

Area of Interest Transition

A valid evaluation of the result of applying the spatial level of detail transition with high detail in an area of interest and lower detail in the background is not a simple task. The dynamic sequence with the moving area of interest must be viewed on a display whose angular size at the eye is the same as that of an operational system. This requires

either a large-screen display or collimated optics. It is then necessary that the evaluator keep his vision centered at the center of the area of interest. Note that, in an actual real-time system, the area of interest will track the observer's vision -- opposite to this evaluation sequence.

To provide a medium which can be used at a number of locations and which will meet the size requirement, a 16mm movie version of the scene was provided, as well as a video tape version. To aid in tracking the center of the area of interest, a small cross at the center has been programmed into the scene (this will not, of course, be present in an operational system).

Evaluation of the dynamic area-of-interest transition on a large screen shows it to be smooth and free of distracting effects. For some of the objects undergoing transition, there is no consciousness that transition is taking place. For the large runway stripes the transition is apparent. Evaluation of these results provides guidance to scene modeling to achieve best results, and indicates that with suitable modeling and application of gradual transition in this manner, the viewer would have no impression of a changing scene.

Gradual Transition Real-Time Implementation

The evaluation scenes were made by generating two separate scenes and then merging them with assigned weighting. This scheme was flexible and fully valid for evaluation, but it was not intended to be applicable to real-time implementation. The very satisfactory evaluation results provided incentive to develop an implementation approach that would be feasible for operational systems.

A current Independent Research and Development (IR&D) project is directed toward developing simulation of translucent faces. These will be used for translucent smoke and clouds, windows, and for efficient and effective simulation of shadows and landing lights. These translucent faces offered an approach to a hardware feasible implementation of gradual transition between two versions of a feature.

This approach was applied to the same ship scene that had been used for evaluation earlier. The faces of one were given a saturation value, the faces of the second were given a different saturation value with the two adding to 100%, and all were processed. Some problems arose that had not been anticipated, but solutions were devised which did not violate the features expected to lead to feasible operational implementation. Scenes matching the earlier results were produced to validate this approach.

Spatial Transition Real-Time Implementation

This is a far more difficult task than whole-object transition. This requires the portions of two versions of a feature to vary from pixel to pixel on the display, in the transition region between the high-detail area of interest and the low-detail background. Attempts to devise an approach which might lead to a feasible operational implementation of this transition were not successful.

Level of Detail Modeling and Transition Criteria

A great deal of insight was gained by the study of techniques used and results obtained with earlier systems. The analysis of these results, combined with consideration of new criteria and modeling approaches, has led to a set of rules and recommendations which could be applied to improve results on existing systems, on future systems without gradual transition, and in particular on future systems incorporating gradual transition.

Edge Efficient Modeling

Early CIG systems had very limited edge processing capacity. This led to extensive effort to model environments which would provide effective training while using very few edges. About the best guidance for efficient modeling is to use examples of past models, both those illustrating good practice and those illustrating poor practice. An example of the latter is one case where a new modeler was modeling a bus for a scene on the non real time scene generation system. Each of the four wheels was closely approximated with a 48-edge representation. It was impossible that most of these could ever contribute to the displayed scene, unless the bus was allowed to fly.

CONCLUSIONS

Gradual Transition

The results of applying gradual transition will be a great improvement in the realism of the display and in reduction of distractions. Although extra edges must be processed during transition, it is probable that transition to higher detail can take place later in a flight when closer to a feature, which will more than make up this loss in edge utilization efficiency.

The translucent face algorithms have not yet been developed to the point to make possible a cost estimate. It is anticipated that the implementation cost will be moderate, since the planned concept does not involve the major part of the high-speed processing hardware.

It is thus concluded that gradual level-of-detail transition of three-dimensional objects, as well as of surface features, should be incorporated in future systems.

Area of Interest Transition

In applying this technique, no improvement of results is possible as compared with using a high level of detail over the entire display. The potential is that by allowing lower detail to be used in the background, a system with lower edge capacity can achieve equivalent results, thus reducing cost. To gain a net savings, the implementation cost must be less than the cost saved by reducing edge capacity. At present this does not appear probable, if implemented using the gradual spatial transition between levels of detail.

An alternate approach to implementing area-of-interest oriented level of detail was devised after the above conclusion was reached. It assumes the system incorporates the gradual transition applied to entire objects or models. In such a system, a level-of-detail control parameter is computed for each object, based on distance, criticality, etc. In this approach to area of interest, the location of an object in the view window relative to the center of the area of interest is added to the factors used in control parameter computation. Thus, as an object moves from the periphery toward the center of the area of interest, it will gradually change from low-detail to high-detail versions. At any time, a given object will all be of a given level, or at a given point in its transition. This will provide the efficiency of concentrating edges where visual resolution is sharp, while still avoiding distracting abrupt changes.

Detail Transition Rules

In past systems detail transition rules considered to be inclusive and valid were designed into the hardware. In use of the systems, it was found that modification of the transition functions were desired. In many cases, it was desirable to change them depending on the scene or the training mission. In future systems the transition control system should be more flexible and more under the control of the modeler and experiment director to facilitate such variation.

Modeling

Effective and efficient modeling can be beneficially applied to any existing or future system -- no equipment or software changes are required. Much can be done to help the modeler, and development effort is under way in this area. Automatic modeling of terrain, working from

elevation source data, is being perfected. A library of edge-efficient models can be called as needed by the modeler. Interactive consoles will make it easy for him to assemble and modify an environment. Software is being developed which will compare the data base being assembled, with the constraints of the hardware with which it is to be used, and inform the modeler of any problem areas.

PREFACE

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This study was initiated by the Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio 45433. The effort was conducted by General Electric Company, Space Division, P.O. Box 2500, Daytona Beach, Florida 32015. Dr. W. Marvin Bunker was the principal investigator for the General Electric Company. Capt. Michael L. Ingalls, of the Simulation Techniques Branch, Advanced Systems Division, was the contract manager for the Air Force Human Resources Laboratory.

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IMPROVED EDGE UTILIZATION STUDY

SECTION 1

INTRODUCTION

1.1 BACKGROUND

The first Computer Image Generation (CIG) system capable of displaying solid objects on raster scan display devices was delivered to the National Aeronautics and Space Administration (NASA) in 1962. It could process and display up to 240 edges per raster line. Its potentially visible edge capacity was also 240 edges. The edge capacity of the vector generator part of the processing was 240 edges. Finally, the maximum number of edges in the entire environment was 240 edges. This arrangement had the merit that there was no danger that any stage of the processing would be overloaded by data received from the preceding stage. However, it was also true that for typical scenes, such as the one shown in Figure 1 taken from this system, a large portion of the edge-per-scan-line capacity was wasted. Processing of 240 potentially visible edges will give a maximum edge-per-scan-line count far less than this for most scenes.

In a CIG system, edge processing capability is expensive. However, the scenes produced by displaying the processed edges provide the visual cues necessary for training. If at any time a portion of the available capacity is not being used, but additional detail could contribute to training effectiveness, then the system capability is not being efficiently and effectively utilized.

For additional insight into this area, consider a system with a 12,000-edge capacity. A house could be modeled, including doors, windows, individual definition of each board in the siding, the roof shingles, etc.

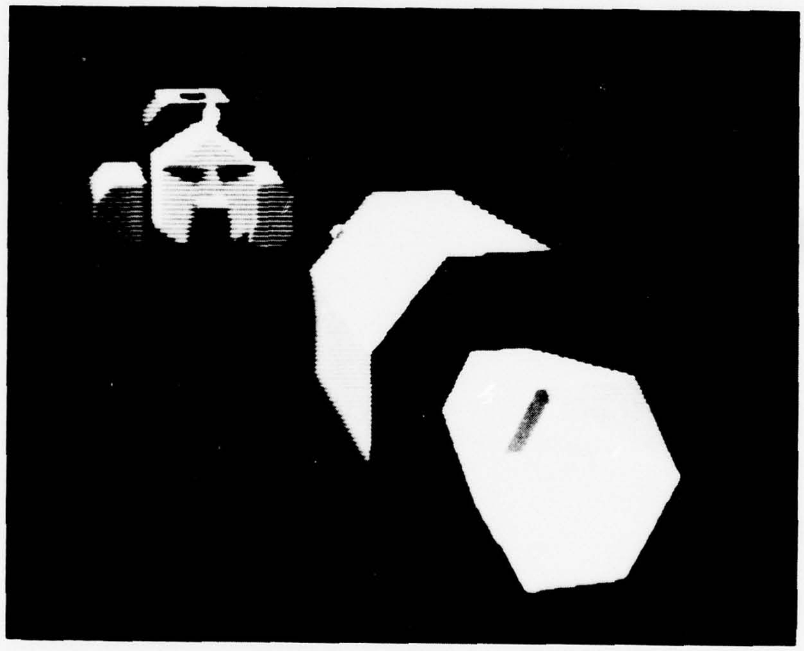

Figure 1. Docking Spacecraft, Early Real-Time System

This could easily be done so that the entire 12,000-edge capacity of the system would be required to display the house, leaving none for roads, fields, vehicles, terrain relief, or other visual cues. This, then, would not represent a desirable utilization of system edges.

Next assume we model the above scene properly, with appropriate allocation of edges to the house and to other scene features. Assume the result uses the full system edge capacity to provide maximum visual detail. Now back up from the scene. It will become smaller in the view window, but will contain the same number of edges -- equal to the system capacity. However, as we back up, additional area is coming into view, and we should see the features contained in this added area.

To obtain edge capacity for processing these nearby features, we must delete some of the edges of the distant features; either by deleting features entirely, or by replacing high-detail versions with lower-detail versions containing fewer edges. This is referred to as level-of-detail (LOD) control. It was incorporated in the second solid-object CIG system, delivered to the Navy in 1972, and it has been used on subsequent systems.

LOD achieves its purpose; however, due to the extreme sensitivity of the eye to abrupt changes in scene detail, the transistions are noticed and detract from simulation realism. When LOD selection is based on obvious criteria, such as distance of a feature or the size of its image on the display, it can happen that a small but critical feature in the highest area of interest of the display will change to lower detail, while peripheral features retain high detail.

1.2 AREAS FOR INVESTIGATION

The experience covered in the historical background above motivated the goals of the Improved Edge Utilization Study.

1.2.1 GRADUAL TRANSITION BETWEEN LEVELS OF DETAIL

This goal requires an attack on the abrupt, highly noticeable, transitions of existing systems. The goal includes generation of scenes and gradual-transition sequences, evaluation of the results, and development of concepts and algorithms suitable for real-time hardware implementation of gradual transition.

1.2.2 AREA OF INTEREST LEVEL OF DETAIL

This goal requires the concentration of edges where they are most needed. In broad terms, this is currently done when a gaming area is modeled. Large numbers of edges are used to provide valid runway markings, with fewer edges for velocity and attitude cues around the airport. However, this effort involves variable LOD on a single display, based on direction of view, with gradual transition between the high-detail target region, and the lower-detail background region.

1.2.3 LEVEL-OF-DETAIL SELECTION RULES

This requires analysis of existing criteria, and the manner in which they are applied. Other criteria not currently used must be considered. Selection and transition rules must be developed to provide improved results, particularly emphasizing applicability to systems employing gradual LOD transition.

1.2.4 MODELING RULES

Ground rules are needed for modeling features to various levels of detail so as to minimize edge utilization and provide acceptable transitions. In particular, these should be suitable for the gradual transition systems.

SECTION 2

GRADUAL LEVEL OF DETAIL TRANSITION

2.1 EVALUATION ALGORITHM

It was essential that the system used to generate scenes and sequences for evaluation be flexible and that there be essentially no possibility of any unknown or unanticipated effects associated with scene generation. To achieve this, the General Electric laboratory static scene generation system was used as follows. A scene was modeled with each feature at the lower of the two levels of detail involved in a transition. For the desired viewpoint and view window definition, the scene simulation was generated, and stored in a solid-state refresh memory -- addressable pixel by pixel. The same scene was then modeled with each feature at the higher of the transition levels of detail. It was placed in a second channel of refresh memory after generation.

Now assume we want to examine a display made up o 25% low detail with 75% high detail. We access the pixels of the two channels of memory containing the high- and low-detail scenes. The outputs of each pixel are combined using the designated ratio, and the composite pixel tones are stored in a third channel of refresh memory. Generating a sequence of such scenes with a changing ratio and recording these on sequential tracks of a time-lapse video disc recorder produce a dynamic gradual transition scene for evaluation.

2.2 EVALUATION SCENE 1.

2.2.1 PURPOSE

The first scene modeled for generation of a gradual transition sequence was intended to validate the programming for producing such scenes, to reproduce the earlier results involving a runway and runway markings, and to produce evaluation sequences for three-dimensional objects with only minor differences in outline between adjacent levels of detail.

2.2.2 DESCRIPTION

Figure 2 shows the higher detail of the two scenes generated. In the center is a runway with runway markings. At the right are three versions of a bus, and at the left are three versions of a cylindrical tank. The edge-counts of these features for this scene are tabulated below:

Table 1

Scene 1 Edges

Feature	High-Detail	Low-Detail
Runway	4	4
Runway Markings	168	-
High Detail Bus	162	-
Medium Detail Bus	36	36
Low Detail Bus	15	15
High Detail Tank	48	-
Medium Detail Tank	24	24
Low Detail Tank	12	12
TOTAL	469	91

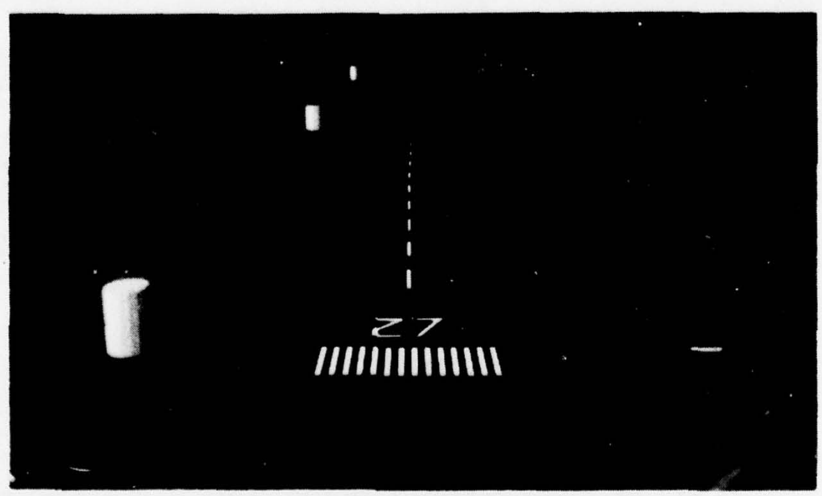

Figure 2. Evaluation Scene 1: High Detail

Figure 3 shows the lower-detail scene, whose edges are also tabulated above.

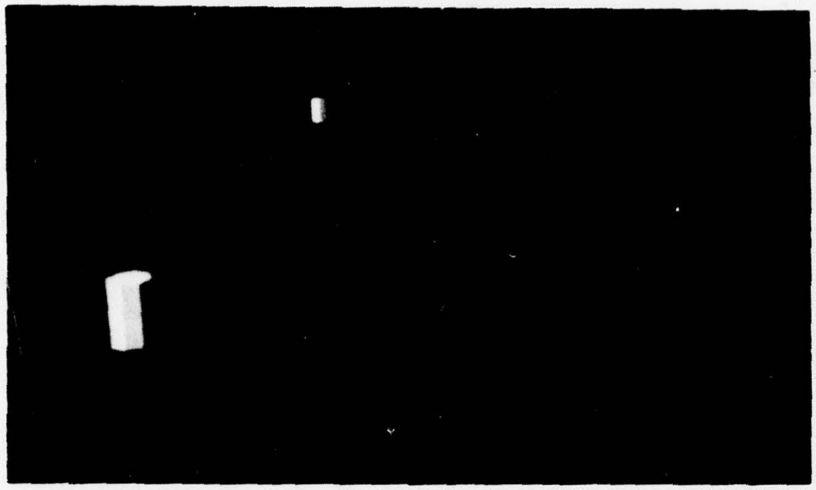

Figure 3. Evaluation Scene 1: Low Detail

2.2.3 RESULT

It is even more true in this study than in most previous CIG studies, that it is essential to view the dynamic sequence to evaluate the effect of what has been done. However, to provide an indication, Figures 4, 5, and 6 show three equally spaced steps in the transition from the low-detail to the high-detail scene. The dynamic effect is of a gradual, almost imperceptible change from one to the other.

2.3 EVALUATION SCENE 2.

2.3.1 PURPOSE

The second test scene was devised to help evaluate an expected problem area -- transitions between models with significantly different image outlines. The worst manifestation of this problem was anticipated when a portion of a feature, present in the high-detail version but not the low-detail, gradually appears against a non-uniform background. Background features might be expected to show through in a very unrealistic manner. The intention was to produce scenes, evaluate the problem areas, and attempt to devise a combination of transition algorithms and modeling rules to produce satisfactory results.

Figure 4. Evaluation Scene 1: 25% High + 75% Low

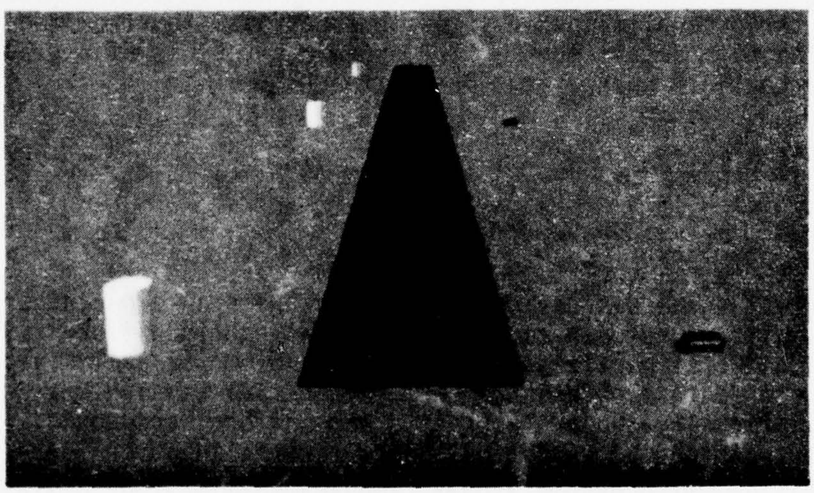

Figure 5. Evaluation Scene 1: 50% High + 50% Low

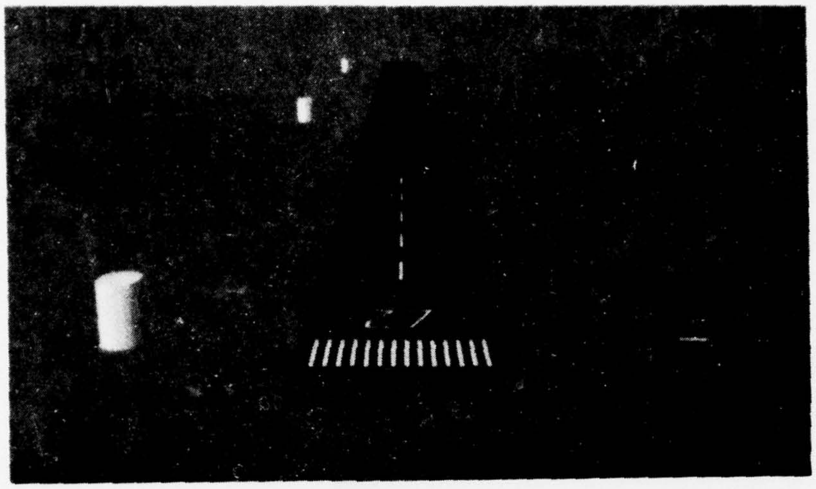

Figure 6. Evaluation Scene 1: 75% High + 25% Low

2.3.2 DESCRIPTION

Figures 7 and 8 show low-detail and high-detail versions of a ship. Significant differences in outline can be noted in the superstructure. The mast of the high-detail version extends above the horizon, so the effect of horizon bleed-through during transition can be investigated. The high-detail version contains 55 edges, and the low-detail version 31 edges.

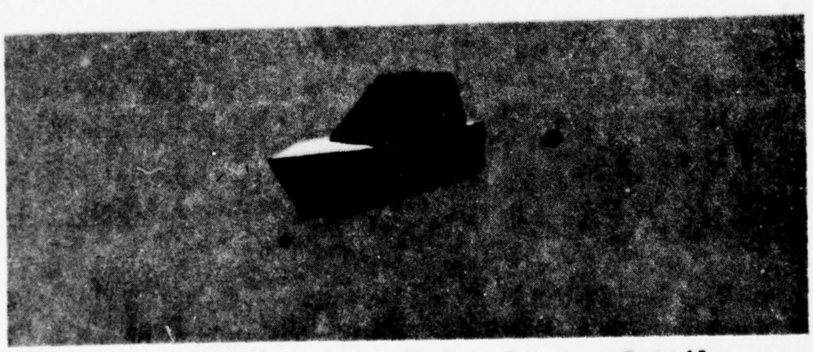

Figure 7. Evaluation Scene 2: Low Detail

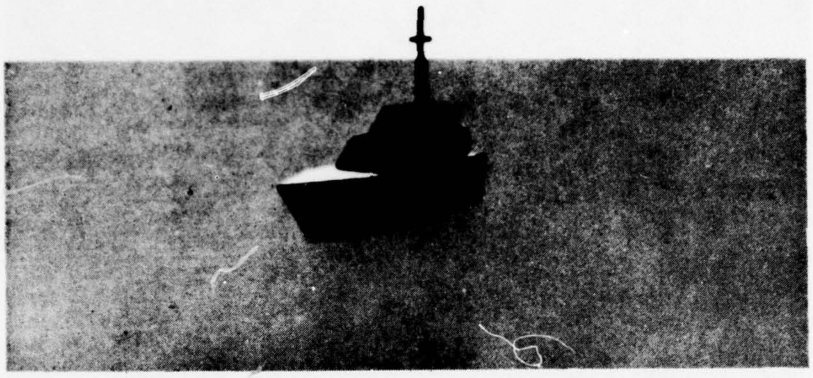

Figure 8. Evaluation Scene 2: High Detail

2.3.3 RESULT

A dynamic sequence of transition from the low-detail scene to the high-detail scene was produced. On viewing this sequence, the first thing looked for was the effect of the horizon bleeding through the mast, and the surprise was the fact that this was not seen. Later, on looking very closely for this one effect, it was found to be present, but only barely noticeable -- and this was something that had been expected to be a major problem area.

This appears to be explained by the mutual inhibition effect in visual perception. This was discovered by H. K. Hartline[1] and reduced to convenient mathematical form by von Békésy[2]. It has previously been applied to aid in understanding of visual effects associated with CIG[3].

---

1. Hartline, H. K. & Ratliff, F., Spatial summation of inhibitory influences in the eye of the limulus. J. Gen. Physiol. 41,1049-1066.

2. von Békésy, G., Neural inhibitory units of the eye and skin, Quantitative description of contrast phenomena. J. Opt. Soc. Amer. 1960, 50, 1060-1070.

3. Bunker, W. M., Applied optical illusions -- A simulation model of eye response helps improve visual scene simulation. Proc. 8th Annual Simulation Symposium, Tampa, FL Mar. 12-14, 1975. pp 181-195.

In Figure 9, the squares represent a row of retinal receptors, rods or cones. For a given receptor, e_i represents the excitation from the scene being viewed; r_i represents the response. The response the brain sees from receptor n is a function of the excitation received by n, modified by an inhibition effect from the other receptors.

$$r_n = k_0 e_n - k_1 e_{(n+1)} - k_1 e_{(n-1)} - k_2 e_{(n+2)} - k_2 e_{(n-2)} - \dots$$

The magnitude of the values of K decreases exponentially with distance from receptor n. This is a well established effect, and a treatment based on the simplified expression above explains both first-order and second-order Mach effects.

n-5	n-4	n-3	n-2	n-1	n	n+1	n+2	n+3	n+4	n+5

Figure 9. Array of Visual Receptors

Figure 10 shows the mast against the sea and the sky. On a scale of 0 for black, to 255 for maximum brightness, the sea in this scene was given a tone of 150, the sky a tone of 220. The face of the mast seen from the selected viewpoint with the specified illumination direction used for these scenes, has a tone of 86. At the halfway point in the transition, the top of the mast has a tone of 153, and the bottom a tone of 118 -- this difference is what was expected to give rise to unrealistic effects.

The "distance constant," comparable to a time constant in electrical circuit analysis, is the distance at which the mutual inhibition effect has decayed to 1/e, or 36.8%, of its initial value. This is of the order of magnitude of 10 arc minutes at the eye[3]. If the size of the mast is of this same order, then we can use a simplified expression to estimate the perceived tone of the mast. Represent excitation and response of mast by e_m and r_m. Represent excitation and response of background by e_b and r_b.

---

3. Bunker, W. M., op cit

$$r_m = k_o e_m - \left[2\sum k_i\right] e_b . \text{ Designate } 2\sum k_i \text{ by } k^*.$$

In the referenced earlier work[3], the following values were obtained:

$$k_o = 2. \quad k_j = -\frac{xp[-j/N] - p[-(j-1)/N]}{2} \quad ; j = 1,\infty \quad .$$

where N is the number of visual receptors in one distance constant. This leads to $k^* = 1$.

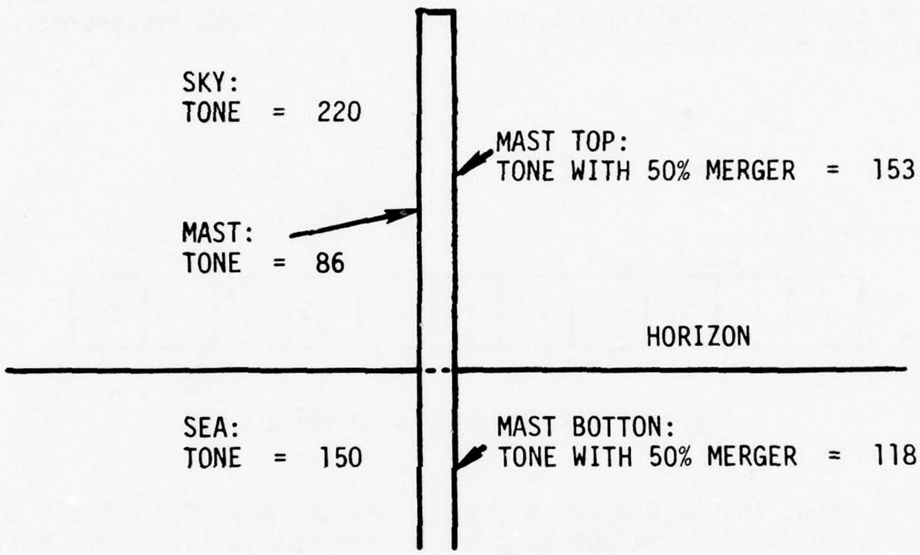

Figure 10: Mast, Sea, and Sky

Now we can apply the mutual inhibition equation to the mast, as it appears against the sky and against the sea. Qualitatively, the brighter the background, the darker a small feature looks as compared with its actual tone.

Against the sky: $r_m = 306 - 220 = 86.$

Against the sea: $r_m = 236 - 150 = 86.$

Based on these results, it is not surprising that when the scene was viewed, no break was seen.

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3. Bunker, W. M., op cit

If the mast was much wider, then one of the conditions of the above analysis would be violated, and the horizon would be visible bleeding through the mast, particularly in the central region of the mast. However, in level-of-detail implementation new features are added to the scene when they are quite small, so the conditions which led to the satisfactory results in this evaluation will be met.

The goal of the above analysis is to provide insight, in a somewhat quantitative manner, to observed effects. It is of interest that if the same type of analysis is applied to the full high-detail scene, with the mast a constant tone, it predicts that the top and bottom will appear of different brightness -- and in fact some observers have been convinced they could see the horizon through the mast in this scene.

For the outline change in the superstructure of the ship, the expected effect was a gradual tonal change from one to the other -- far less perceptible than an abrupt change. The perceived effect verified this expectation, but the result approximated the effect of a gradual spatial transformation from one outline to the other. This was unexpected, and quite satisfying.

Figures 11, 12 and 13 show the 25%, 50% and 75% points in the gradual transition, in an attempt to illustrate the total gradual transition effect. The success of this attempt will depend on the fidelity of the photographic and printing processes. For example, if contrast control is such that everything from light gray to white is printed as white, then the entire top of the mast on the 25% version will disappear, completely invalidating the illusion to be achieved.

Figure 11. Evaluation Scene 2. 25% High + 75% Low

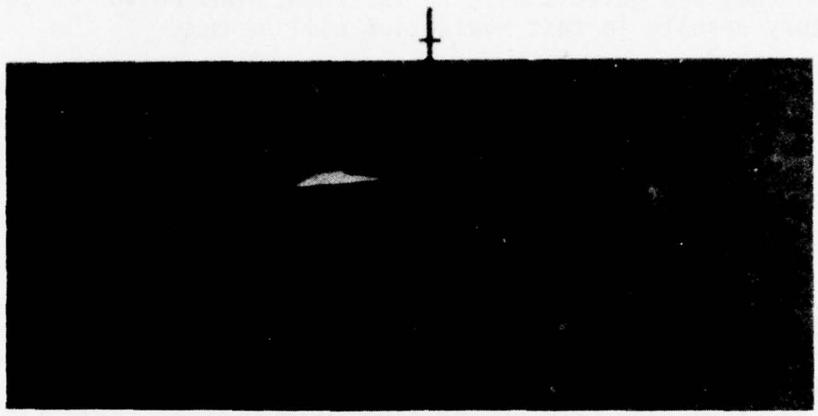

Figure 12. Evaluation Scene 2: 50% High + 50% Low

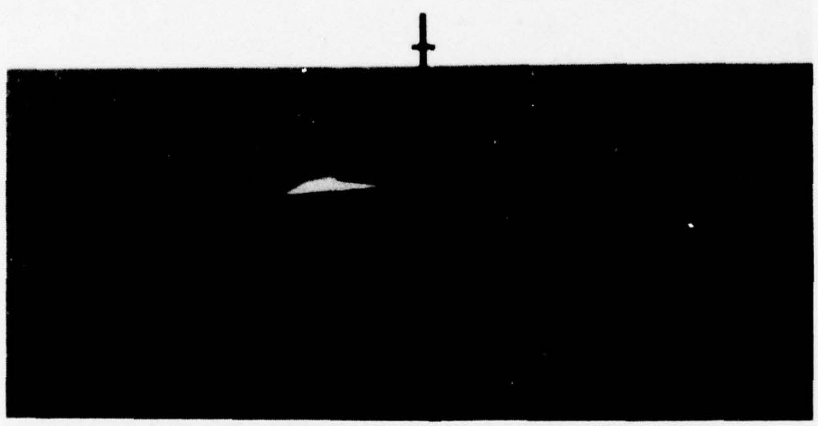

Figure 13. Evaluation Scene 2: 75% High + 25% Low

2.4 EVALUATION SCENE 3

2.4.1. PURPOSE

Although evaluation scenes 1 and 2 showed the effect of gradual transition between levels of detail, they did not involve movement of either the observer or of scene models. In an actual system, the transition will take place while there is motion, and as a result of this motion. While such motion could have been added to one of the scenes described, it was felt desirable to plan a scene that would give answers to additional questions.

The visual effect of transition at different view-window image sizes is important. The larger the size at which transition can be satisfactorily implemented, the greater the effect on edge efficiency. The scene was therefore planned to change from one detail to another at three different image sizes.

For direct comparison with the merging displays, the same scene should show the same models, but with no transition -- computed to high detail at all ranges.

For further comparison, "before and after," it should show abrupt transition taking place.

2.4.2 DESCRIPTION

Figure 14 shows a view window layout for discussion of this scene. In the center zone, at C1, C2, and C3 are identical models of an aircraft, at increasing distances from the observer, so they are of decreasing size on the display. The left zone and the right zone of the display contain the same aircraft, at the same set of distances, as the center zone.

As we fly toward this group of aircraft, those in the left zone transition gradually from a low-detail (100-edge) version, to a high-detail (289-edge) version. The transition is at the same time for all three, so that it occurs for three different view window image sizes.

In the right zone, transition occurs abruptly, at the instant when the center group is going through the 50% transition point.

The aircraft in the center group are computed at high detail for the entire flight -- there is no level-of-detail transition.

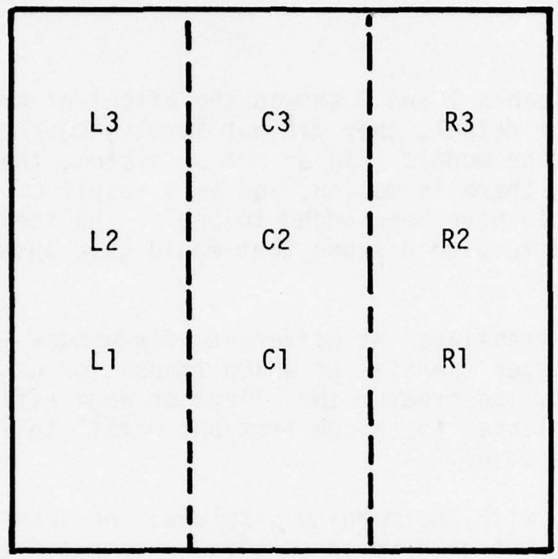

Figure 14. Evaluation Scene 3 Layout

2.4.3 RESULT

The purpose of this evaluation sequence was not to answer a specific question as to whether an algorithm was valid or an effect satisfactory. It was to provide comparative evaluation scenes of gradual transition, abrupt transition, and no transition. When gradual transition is compared with no transition, it is true that the gradual transition can be seen, even on the smallest image, if the viewer is looking for it.

When gradual transition is compared with abrupt transition, it is noted that even for the smallest image, the abrupt transition is quite apparent, whereas even for the largest image, the gradual transition is graceful and unobtrusive.

Figures 15 through 22 show a group of photographs from the dynamic flight sequence. It will be noted there is a period of flight before transition starts and a further period of flight after it is complete. Table 2 summarizes the information.

Table 2

Flight Sequence Snapshot Data

Figure	Percent Low Detail	Percent High Detail	Distance From Aircraft Near	Middle	Distant
15	100	0	300	600	1200
16	100	0	258	558	1158
17	75	25	230	530	1130
18	50.01	49.99	200	500	1100
19	49.99	50.01	198	498	1098
20	25	75	170	470	1070
21	0	100	140	440	1040
22	0	100	100	400	1000

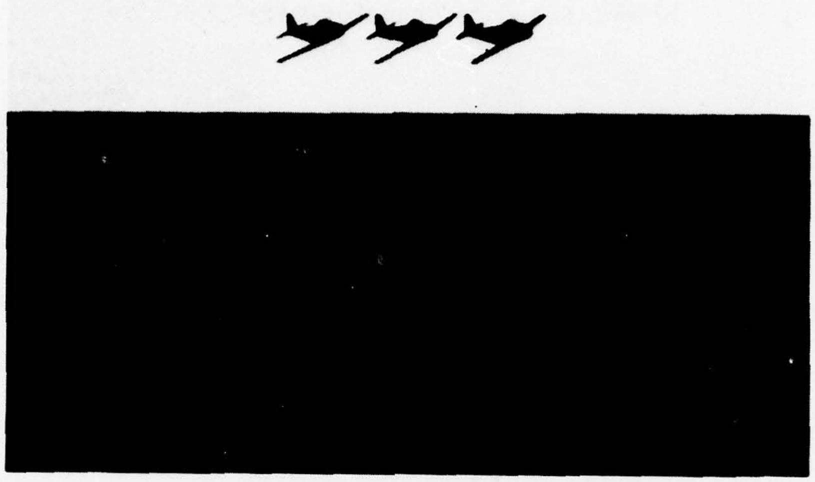

Figure 15. Dynamic Flight Sequence Scene 1.

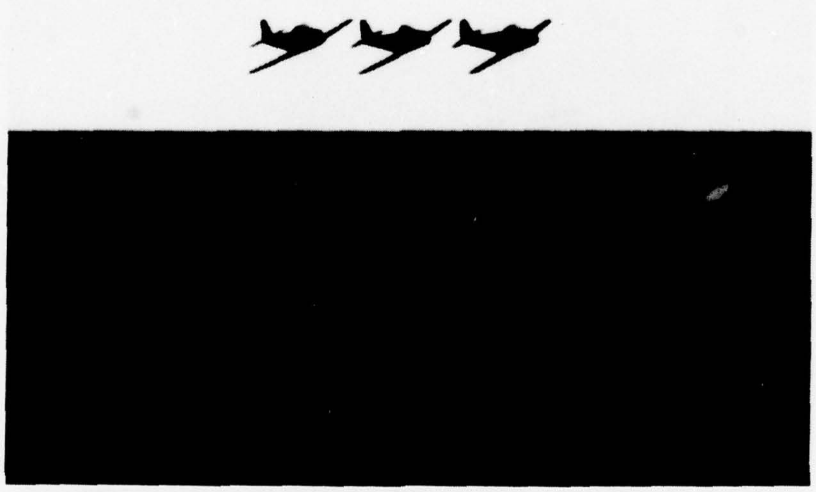

Figure 16. Dynamic Flight Sequence Scene 2.

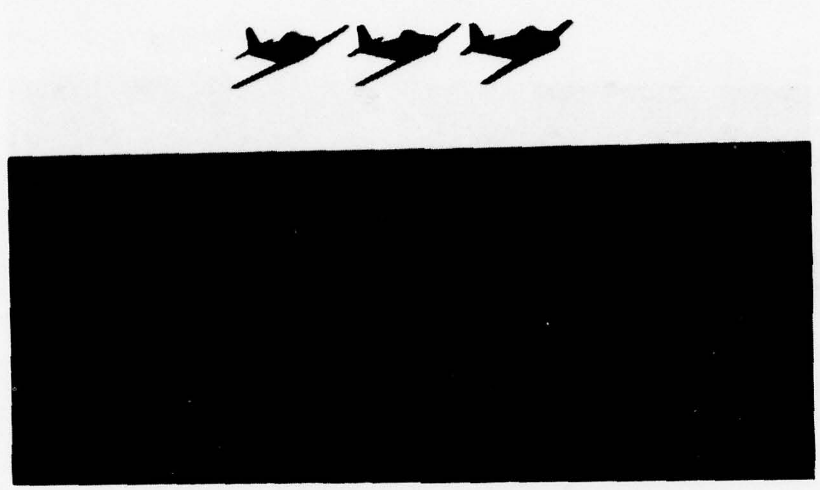

Figure 17. Dynamic Flight Sequence Scene 3.

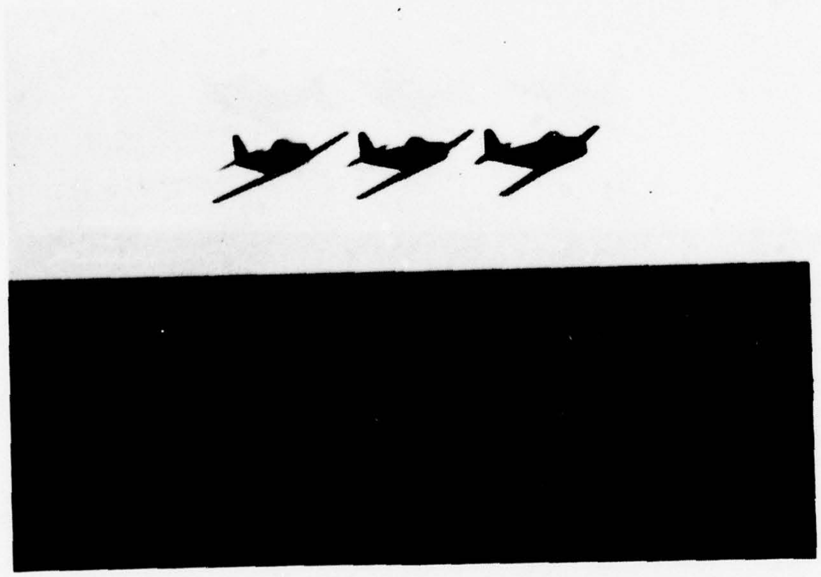

Figure 18. Dynamic Flight Sequence Scene 4.

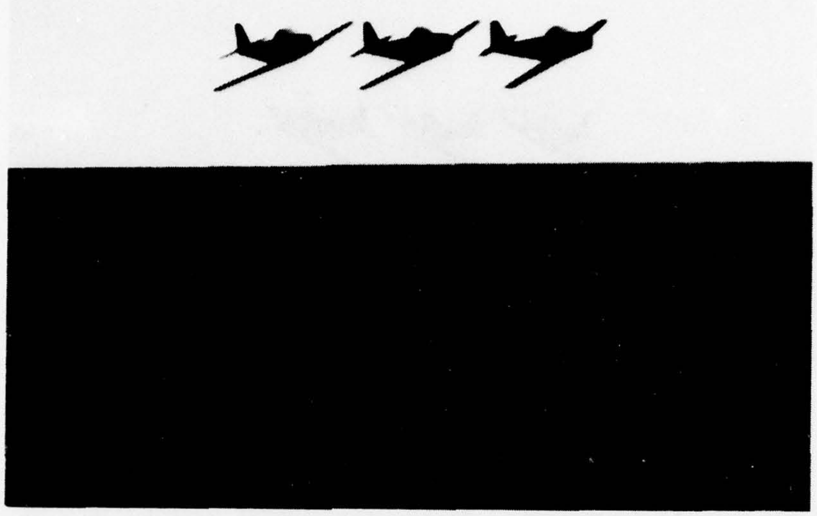

Figure 19. Dynamic Flight Sequence Scene 5.

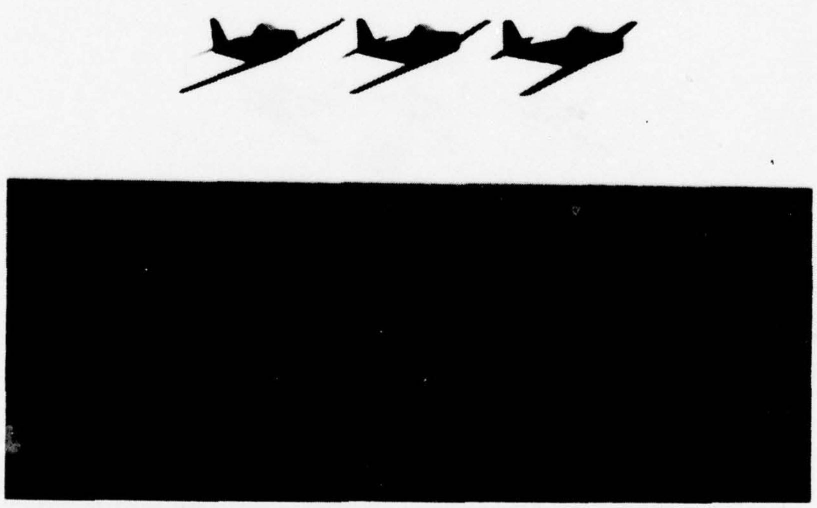

Figure 20. Dynamic Flight Sequence Scene 6.

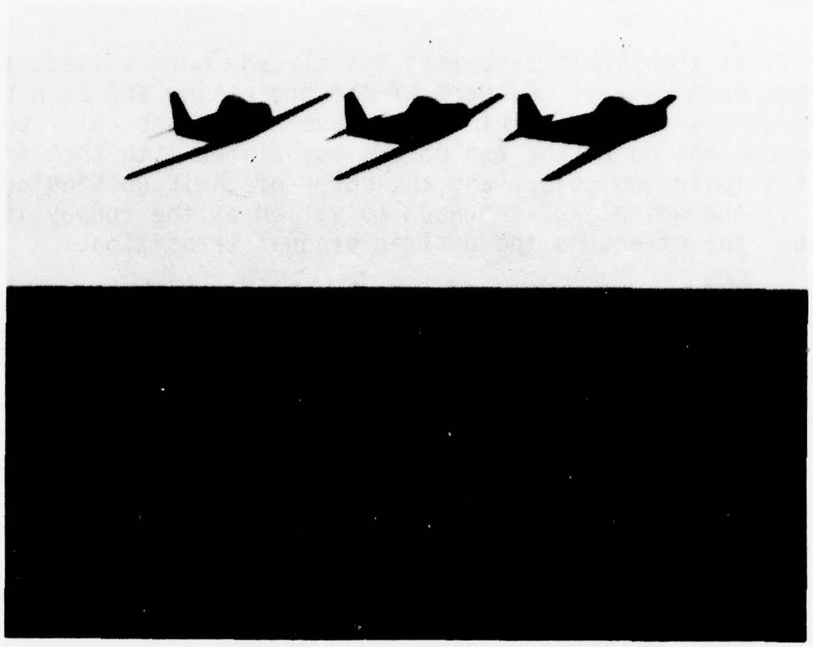

Figure 21. Dynamic Flight Sequence Scene 7.

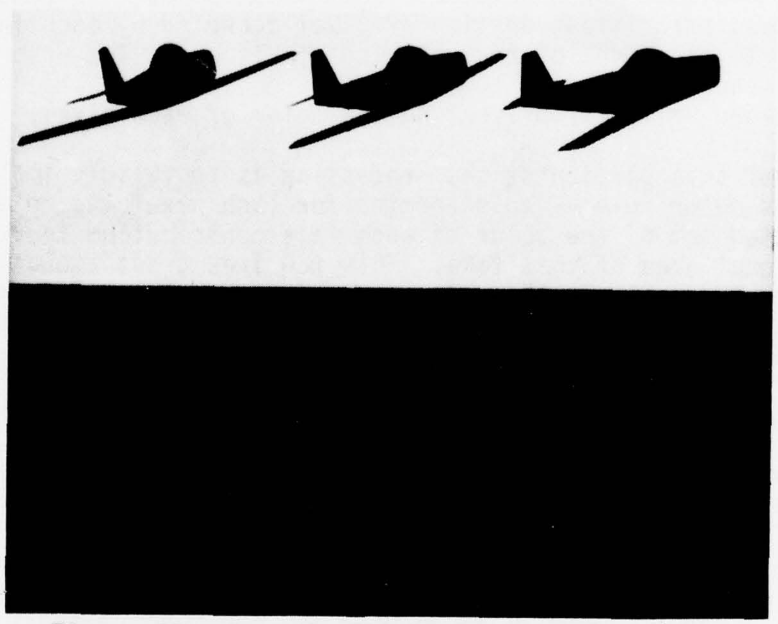

Figure 22. Dynamic Flight Sequence Scene 8.

2.5 HARDWARE FEASIBLE ALGORITHM

Consider first the simple case that has already been solved, typified by markings on a runway. As part of the processing for each scene, the faces representing these markings can have their face color set to a weighted combination of the two colors associated with them in the data base; i.e., their own color, and the color of their unchanging background. If the weighting is gradually varied as the runway is approached, the effect is the desired gradual transition.

This approach is not applicable to three-dimensional (3D) objects. Not only does the background for such an object vary from scene to scene, it will in general change from one scan line to another, and even part way through a face on a given scan line. Thus no scheme of changing a face color applicable to an entire scene can be expected to work.

Consider next the scene processing that occurs for each scan line. Active edges are selected, defined for the current scan line, and ordered from left to right. This part of the processing is relatively simple, straightforward, and does not require large amounts of hardware.

The next step in the processing is the priority resolver. This considers the edges one at a time as they arrive from the orderer. Where a pixel contains more than one edge, their relationships must be considered -- their faces, priorities, portion of pixel occupied by each face, effect on pixels to the right of the entering pixel, etc. The priority resolver sends information to the video processor from which it can produce video validly representing the color of each pixel.

The goal of this portion of the processing is to validly implement the area times color rule -- to determine for each pixel the color that is the weighted sum of the color of each face contributing to it, times the factional area of that face. This requires great amounts of very high speed processing. These processes are the most difficult to implement with full validity for all combinations of edges and faces. Now we must add an additional factor. For each face we must consider not only the area and color, but where it is on its transition curve. In considering what would be required to implement gradual transition in the priority resolver, no concept was devised which had sufficient promise of being feasible to justify even trying to block out implementation details.

A 1978 Independent Research and Development (IR&D) task has as its goal the development of feasible techniques for real-time implementation of translucent faces. These will be used for the obvious applications -- smoke, clouds, windows, etc. In addition they are expected to be very useful in other functions. Consider the shadow of a building falling across a region of surface containing a number of faces representing

lawn, sidewalk, street, etc. In the past it has been necessary to define a set of separate faces, each with the computed shadowed color of the underlying face, and process these faces and edges to produce the scene with the shadow. Translucent face capability makes it possible to define a single face with appropriate color and saturation and thereby achieve the same effect.

A concept was devised which offered promise of leading to real-time feasible hardware implementation of translucent faces. The idea then occurred of using translucent faces for implementation of gradual transition. Suppose we simultaneously process all faces of both the low-detail and the high-detail versions of a model such as the ship in evaluation scene 2, but give the high-detail faces 25% saturation and the low-detail faces 75% saturation. The results should be the same as those illustrated in earlier scenes.

This approach appeared to offer the best promise of leading to hardware-feasible gradual transition. Effort was therefore accelerated on the translucent face task so that it could be applied to gradual transition, to verify the feasibility of this approach.

2.5.1 TRANSLUCENT FACES

The key factor of the translucent face algorithm, which gives confidence that it will be feasible in operational systems, is that it does not involve the priority resolver or video processor -- the large, complex part of the line-rate and element-rate processing. Rather, it intercepts the stream of edges between the orderer and the priority resolver, it modifies this set of edges, and it then sends the modified set of edges on to the priority resolver for standard processing. The result is valid simulation of the scene with a portion seen through a translucent face.

2.5.1.1 Type 1 Modification

In the following, T designates tone, or intensity. "0" represents black, "255" is brightest white. J has its normal meaning of pixel number along a scan line.

Figure 23 shows part of a scan line. Edge 6 starts face 17, a solid face with a tone of 100 and $dT/dJ = 0.5$. Edge 7 starts face 4, a translucent face with tone = 20 and $dT/dJ = 0$. A type 1 modification consists of changing the tone and dT/dJ associated with an edge starting a translucent face. Assume face 4 has saturation of 40%. Then the tone associated with edge 7 is changed to $(.4 \times 20 + .6 \times 100) = 68$, and dT/dJ is changed to 0.3. In later processing, when the priority resolver encounters edge 7, it will have the values for face 17 seen

through face 4. In general, there can be more than one face behind the start edge of a translucent face. The algorithm must use the highest priority face of those behind the edge.

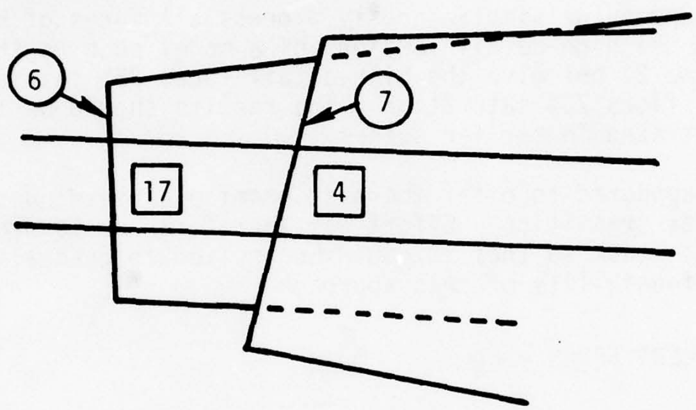

Figure 23. Configuration Requiring Type 1 Edge Modification

2.5.1.2 Type 2 Modification

In Figure 24, edge 8 starts face 15, which has a tone of 200. At this point, the tone on the scan line must change to 128. However, we cannot just change the tonal information associated with edge 8. Note that at edge 9, we "fall off" the translucent face, and edge 8, with its unchanged original information, will be needed by the priority resolver to determine the fallback information. One approach which might be considered would be to modify edge 9 in this pre-priority-resolver edge modification function, so it would contain the fallback data. Such thinking could make this edge modification function as complex as the priority resolver itself -- this we want to avoid.

The type 2 modification, applicable to an edge which has a translucent face in front of it, involves creation of an additional edge for the scan line, spatially identical to the edge initiating the modification, with tonal information reflecting the combination of the translucent face and the face to the right of this edge, and with face-left number and face-right number both that of the translucent face.

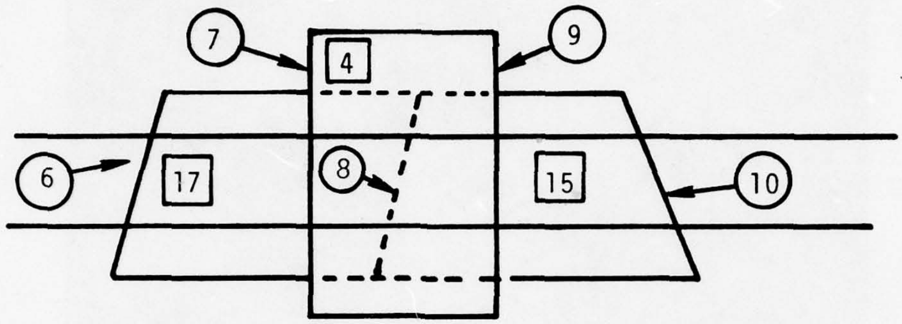

Figure 24. Configuration Requiring Type 2 Edge Modification

2.5.1.3 Initial Results

A program was written which would read the file of edges from the orderer, have access to a "face saturation file," modify edges as described above, and replace the edge file with the modified information. This was then accessed and processed by the priority resolver, for scene generation.

Figure 25 shows a test scene containing a checkerboard background to provide a variety of combinations of edges for algorithm validation and to provide a basis for critical evaluation of the translucence effect. The ground has a tone of 120, bright squares are 150, and dark squares are 90. Both translucent faces have an assigned tone of 60. The one on the left has a saturation of 30%, and the one on the right a saturation of 60%. This scene shows that the desired effect was achieved.

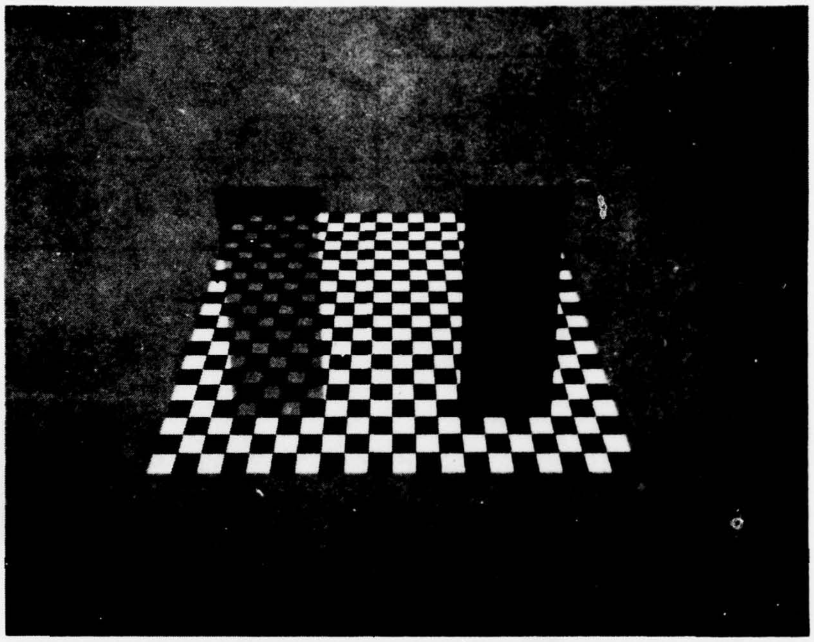

Figure 25. Translucent Face Simulation

2.5.1.4 A problem -- and a Fix

A scene was modeled in which a group of intersecting spheres was intended to simulate translucent smoke. There was an undesirable effect. The region of overlap, illustrated by the lens-shaped area on Figure 26, was much darker than the rest of the smoke. The algorithm as previously described gives the expected results for a scene in which a given area contains only a single translucent face, but when images of translucent faces overlap on the view window this darkening of the overlap region is produced. It might be noted that this is valid simulation of the effect of actual overlapping translucent faces.

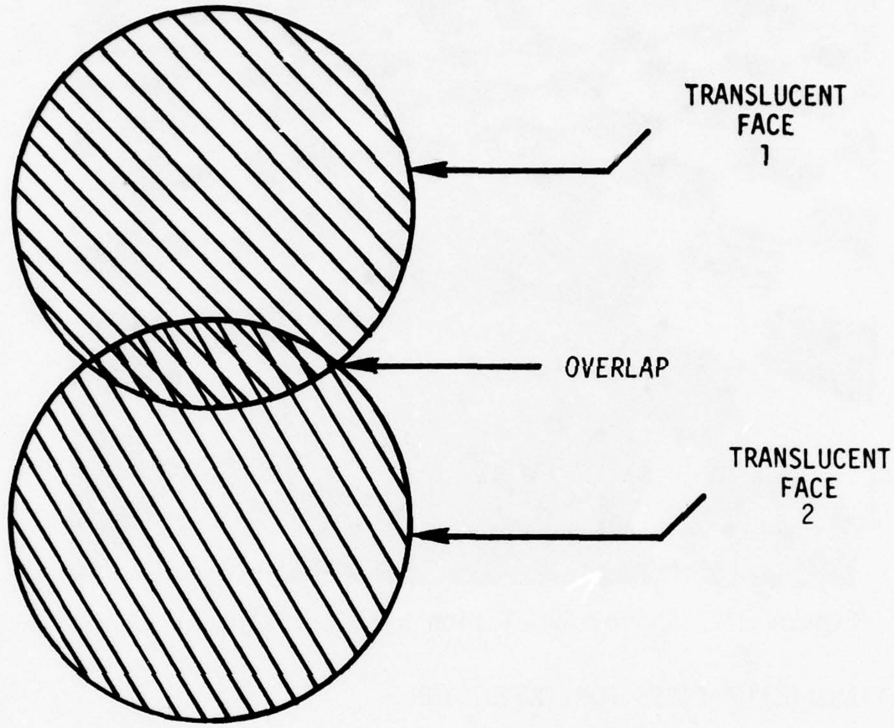

Figure 26. Effect of Translucent Face Overlap

A simple algorithm modification allowed proper handling both of actual overlapping faces, and of those which overlap as spatially defined (such as the smoke), but where the desired effect is that of a single translucent face in the overlap region. Both of the faces representing the spheres belong to the same model in the scene. The edge modification routines check the model number of an edge for which a modification is being considered, and they check model numbers of faces which are candidates for controlling the modification. A face is not allowed to cause modification of an edge from the same model.

Figure 27 shows a scene containing a plume of smoke, generated after this modification. It also illustrates the use of translucent face simulation for shadowing. The shadow faces have an assigned tone of zero, and saturation of 40%.

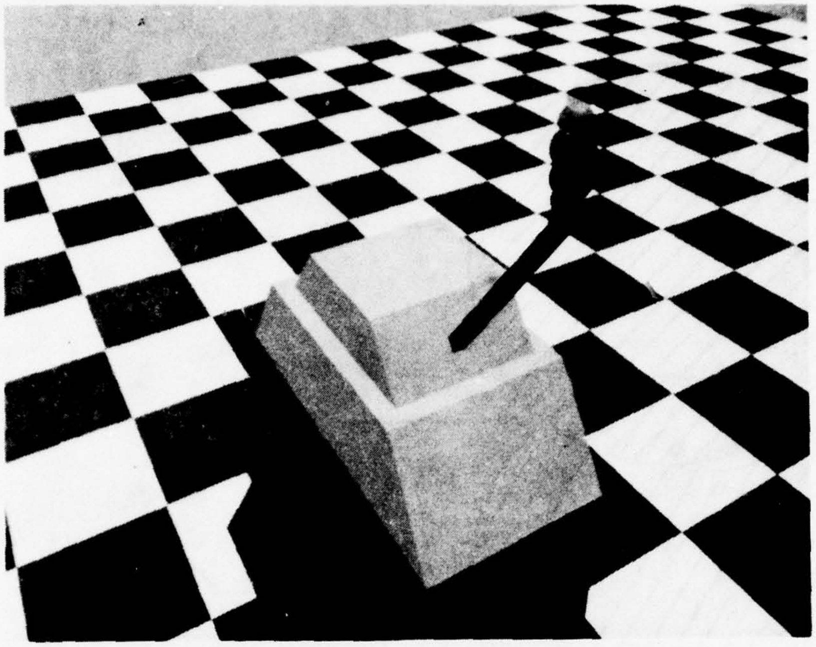

Figure 27. Shadow Simulation with Translucent Faces

2.5.2 TRANSLUCENT FACES FOR TRANSITION

Following development and validation of algorithms for simulation of translucent faces, the next step was to apply these algorithms to achieve the effect of gradual transition between levels of detail.

The high-detail and low-detail versions of the ship were used to form a single data base, and were processed simultaneously. All faces of the high-detail ship were given a saturation value of 25%, and low-detail faces were given saturation of 75%. All high-detail faces were placed in the face priority list, followed by the low-detail faces. The results were unsatisfactory. The light-toned deck of the ship showed through the darker colored faces of the superstructure.

The problem will be discussed with reference to Figure 28. Some high-detail faces are labeled in (a), some low-detail faces in (b), and a combined drawing shown in (c). Referring to (c), consider a ray coming from the left, and piercing faces H4, L2, H5, and L3. Note that H4 and L2 are dark; H5 and L3 are light. In priority order, in the pixel which defines this ray, we have dark H4, light H5, dark L2, and light L3. Thus we see H5 through H4, which gives the effect of the deck showing

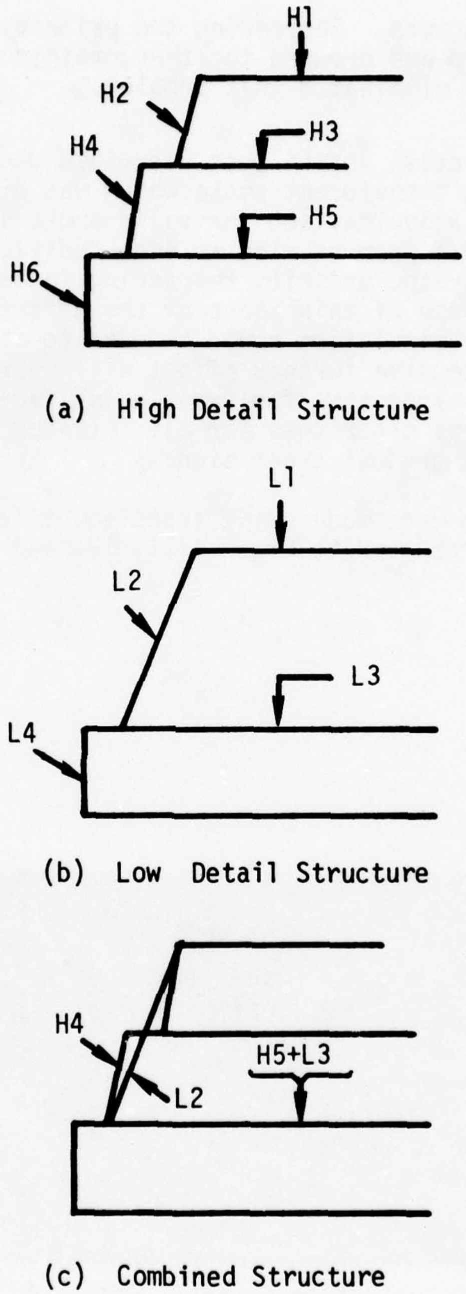

Figure 28. Translucent Faces for Transition

through the superstructure. Reordering the priority so that the faces which are to be merged are grouped together, rather than all faces of a given detail level, eliminated this problem.

The problem and corrective action just described occurred prior to the problem in simulating translucent smoke which was discussed in 2.5.1.4. The algorithm modification devised for valid smoke simulation, preventing faces of the same model from causing an edge modification, might eliminate the need for the priority reordering in implementing gradual transition. The purpose of this phase of the effort was to validate that translucent face simulation could be used to achieve the gradual transition goal. Extensive further effort will be required to define the minimum-hardware algorithms for translucent face simulation, and to validate this set of algorithms for all intended uses of translucent faces in implementing gradual transition.

Figures 29, 30 and 31 were made using translucent faces for gradual transition. They correspond to Figures 11, 12, and 13 from evaluation scene 2.

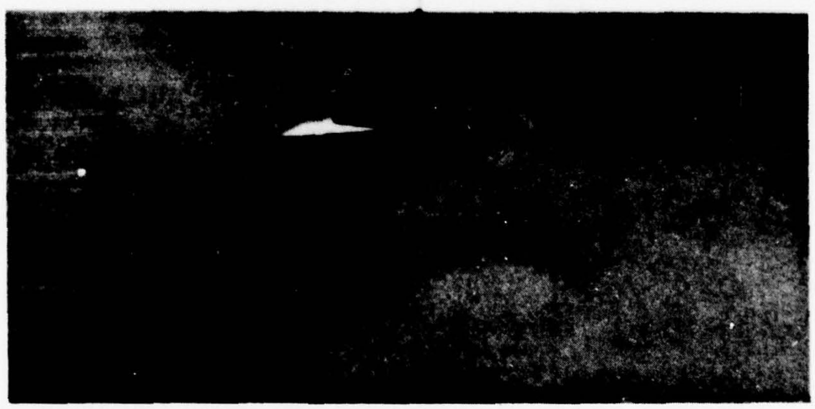

Figure 29. Evaluation Scene 2, 25% High + 75% Low, Simulated with Translucent Faces.

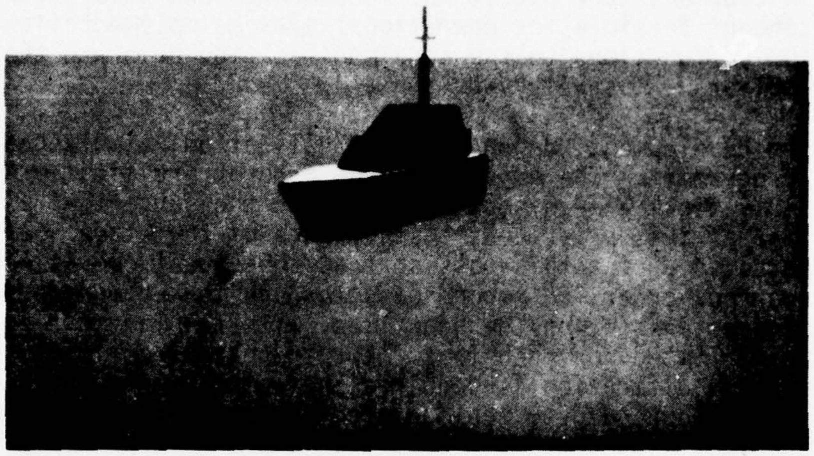

Figure 30. Evaluation Scene 2, 50% High + 50% Low, Simulated with Translucent Faces

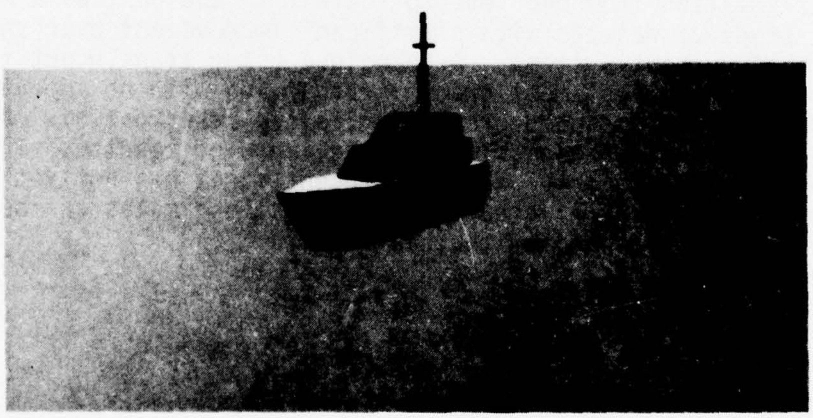

Figure 31. Evaluation Scene 2, 75% High + 25% Low, Simulated with Translucent Faces

2.5.3 ALGORITHM DEVELOPMENT STATUS

Work on the translucent face simulation concept was carried to the point that scenes could by made, indicating it to be a satisfactory technique for implementing gradual transition between LODs. As the algorithm development took place, the fundamental characteristic which makes the concept feasible for operational system implementation -- the isolation of functions to the edge modification prior to the priority resolver -- was retained.

For algorithm development, debugging, and validation, a multipass scheme was programmed. The edges from the orderer are first examined to determine if there are any out of order, in the sense that a stop edge of a face arrives prior to the start edge of that face. If so, they are reordered during this pass so that subsequent operations can assume the correct order. A second pass through the edges produces a list of the faces present on the scan line, with the leftmost point and rightmost point listed for each face. A third pass identifies the edges for which modification is required and computes the tones or intensities to be appended to the modified edges. A final pass makes the modified edges and writes a modified edge file for priority resolver use. Subsequent algorithm development will be required to work out the bookkeeping necessary to perform all required functions in one pass, or two at the most.

2.6 GRADUAL TRANSITION - CONCLUSIONS

A gradual transition from one level of detail to the next as a mission progresses produces results with significant improvement over the abrupt transitions of current systems. A technique using translucent faces makes it possible to implement gradual transition with no impact on the major functions of high-speed processing; hence, the cost of implementation should be quite reasonable, for the improved results. The development of algorithms for the translucent faces has not yet progressed to the point where actual hardware cost estimates can be made, but this effort is planned for the near future.

SECTION 3

DETAIL CONTROL BY AREA-OF-INTEREST

Consider a system in which all portions of all view windows have "standard" level of detail, i.e., high detail for nearby features, with progressively lower detail for more distant features. Because of the eye's small region of sharp vision, most of this detail is wasted. In fact, according to one study, "... the human visual capability can be represented by about 130,000 resolution elements, provided that these elements are sized non-linearly according to the eye acuity function ..."[4]

There are a couple of approaches to determining the location of the area of interest. In same cases, i.e., air-to-air combat or bombing missions, it can be assumed to be centered at a target. In other cases, a sensor of some type can be used to determine the orientation of the head, and the high-detail region can be made large enough to account for the variation in vision direction relative to head position.

Now, if we use lower level of detail features outside the region of sharp vision, there is the potential of equivalent training performance with a lower-edge-capacity, and hence a lower-cost CIG system.

As stated above, this would be quite simple to implement. Merely use the relation between a feature's position and the center of the area of interest as a parameter in level-of-detail transition control. However, this would result in abrupt detail transitions as the point of view changed, and the eye is extremely sensitive to these abrupt changes even when they occur outside the region of high-resolution vision. On the other hand, if we can achieve a gradual spatial change from high-detail features in the area of interest to lower-detail versions elsewhere, then the results might be quite satisfactory.

This part of the study thus must address two questions. Will the subjective effect of scenes with the variable level of detail based on area of interest be equivalent to a reference system with standard LOD everywhere? Second, assuming the answer to the first question is yes, will the saving due to the lowered edge requirement exceed the additional cost of implementing area-of-interest detail transition in an operational system?

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4. Diel, V. E. Variable acuity remote viewing system, NAECON '76 Record, pp 663-668.

3.1 EVALUATION ALGORITHM

For evaluation scenes, two separate scenes were generated, one high-detail and one low. These were stored in two channels of the refresh memory. Then, to make the final scene, the digital video was read from these two channels one pixel at a time, combined, and stored in another channel of memory. This is the same technique that was used for the gradual transition scenes. The difference is in the combining algorithm.

The combining algorithm provided for specification of the center of the area of interest, the high-detail region size (expressed in angular terms or in pixel dimensions), and the transition region size. All pixels within the bounds specified by the high-detail size were made 100% from the low-detail scene. As the transition region was crossed, the ratio was gradually changed from full high detail to full low detail.

Dynamic sequences were produced by moving the center of the area of interest in a path in the view window.

3.2 SCENE EVALUATION

When looking at a scene with gradual spatial transition, one can note that the transition is smooth, without any artifacts created by the processing. The high detail can be seen in the appropriate region of the display and the low detail elsewhere.

In an operational system, the high-detail region tracks the vision of the observer. The goal of the technique being evaluated is that the observer will be unaware that low-detail regions or transition regions exist. To evaluate the test sequences with any degree of validity, it will be necessary to view them on a display system which produces scenes with angular size at the eye which is the same as an operational display system -- a large-screen display. It will then be necessary for the viewer to track the high-detail region as it moves on the screen. If he accomplishes this tracking by identifying which portions of the display are high and which are low, this will in itself invalidate the evaluation.

It is sometimes difficult to locate the center of the high-detail region, even with close examination. Figure 32 shows an area-of-interest detail scene. Figure 33 is the same scene with a small cross identifying the exact center of the high-detail region. The nature of the scene, with the larger runway markings in the lower part of the scene, causes a significant error in the subjective location of the high-detail region, when it is selected from Figure 32. This cross moving on the screen has been added to the evaluation sequences. The sequences have been processed as 16mm movies so they can be projected on large screens for valid angular size in evaluation.

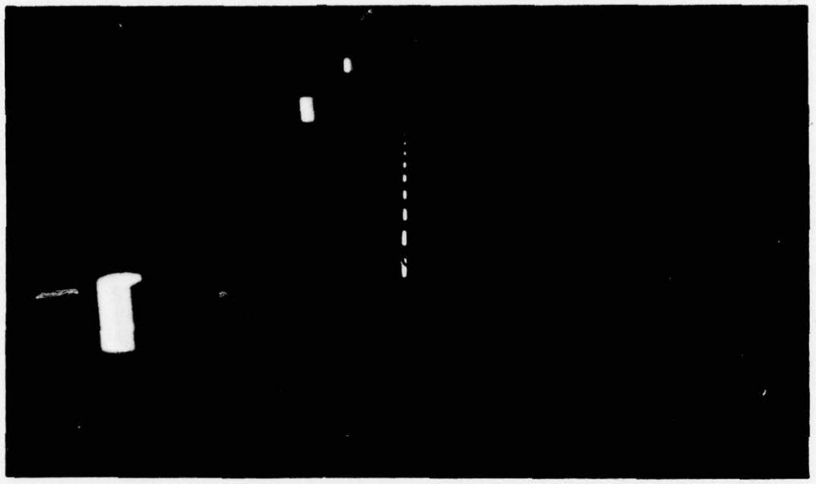

Figure 32. Area-of-Interest Scene Without Center Locator.

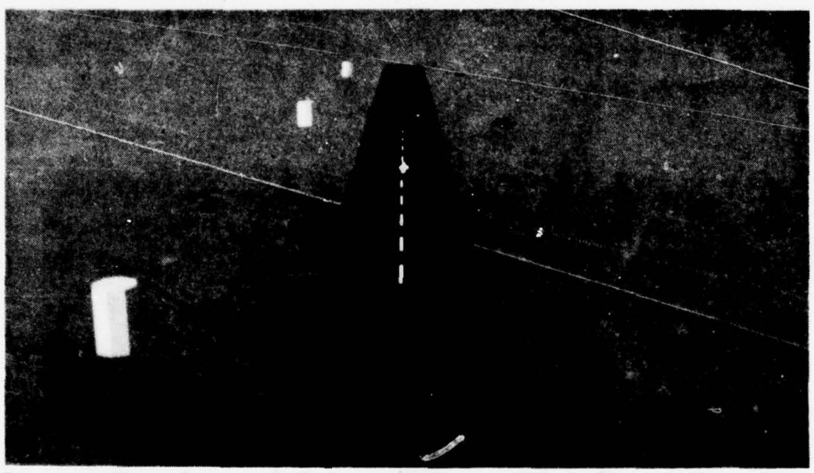

Figure 33. Area-of-Interest Scene With Center Locator.

3.3 EVALUATION SCENES

For area-of-interest evaluation scenes, it is necessary that the size of the high-detail region be sufficiently small relative to the full view window that this region can move around on the view window to a significant degree. It is necessary that the high-detail region be sufficently large that the lack of detail outside this region will not be preceived when the gaze is directed at the center of the area of interest. Further, it is necessary that the width of the transition band be sufficiently large as to eliminate any abrupt-transition effect. While extensive experimentation would be required to establish optimum values, the sizes chosen are believed to meet these requirements. The scene was computed to a 60° vertical by 75.2° horizontal field of view, to give the standard 4 to 3 aspect ratio. The high-detail region has a diameter of 20°. The transition region extends from this to a diameter of 30°. All scene features outside the 30° diameter are shown in low detail.

Figures 34 through 38 show selected scenes of a sequence through the runway data base.

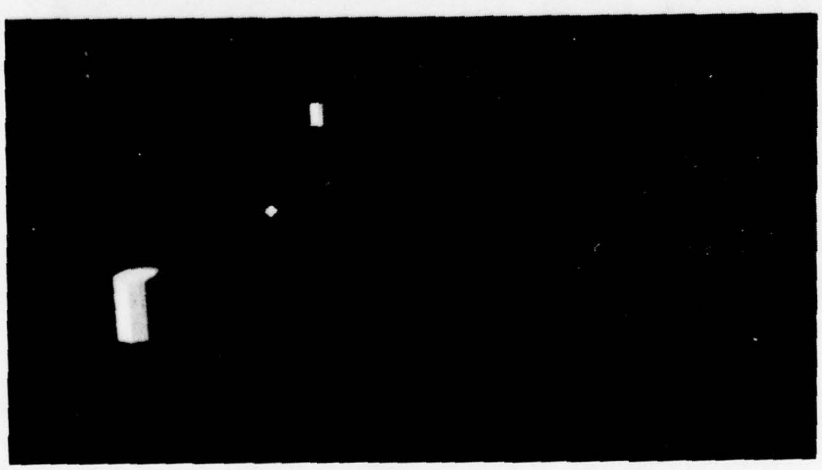

Figure 34. Area-of-Interest Transition, Scene 1

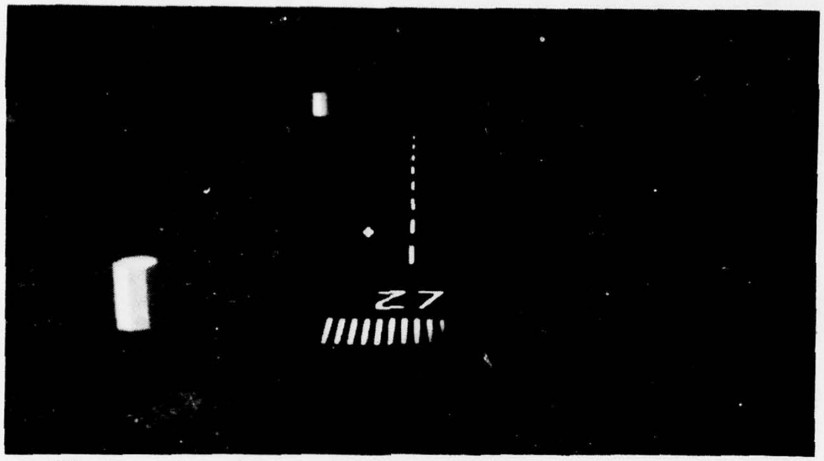

Figure 35. Area-of-Interest Transition, Scene 2.

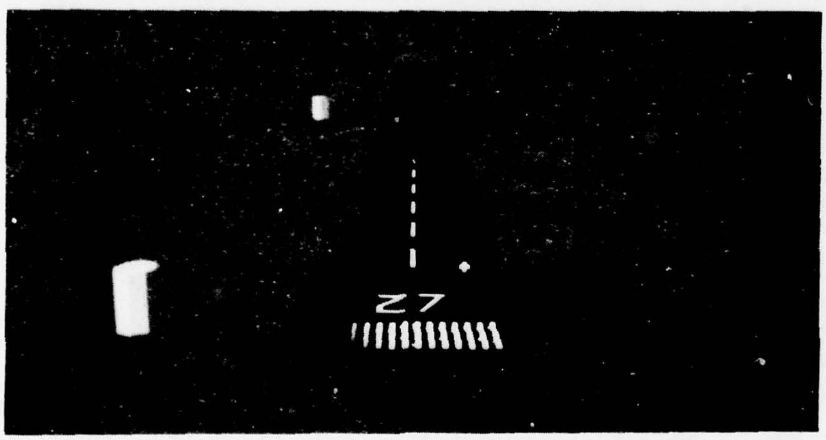

Figure 36. Area-of-Interest Transition, Scene 3.

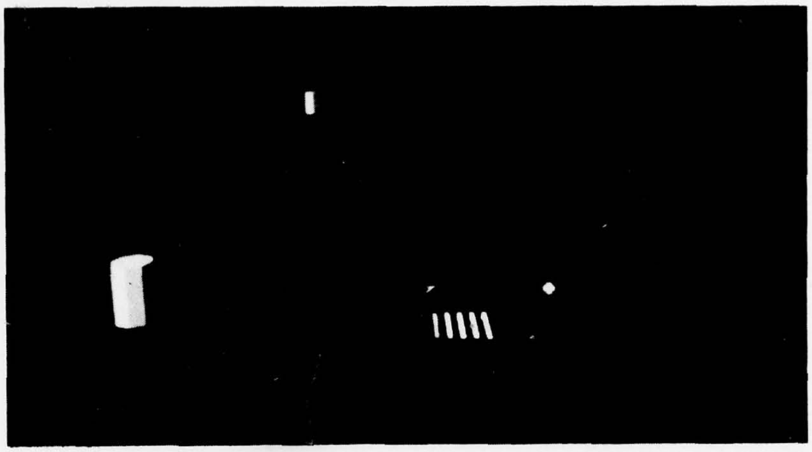

Figure 37. Area-of-Interest Transition, Scene 4.

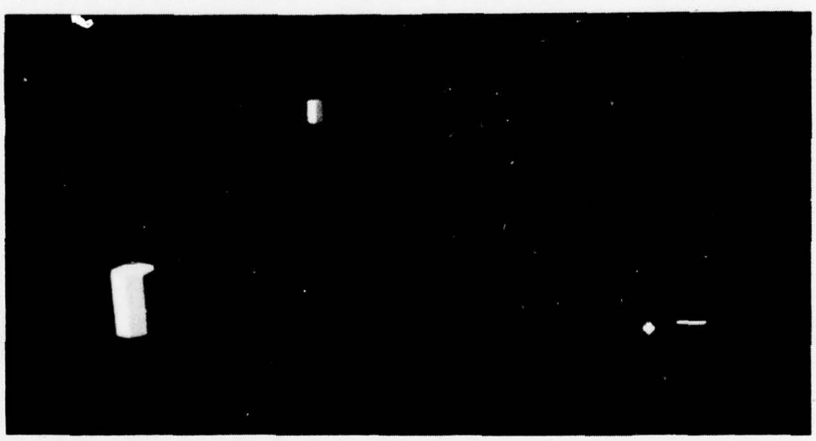

Figure 38. Area-of-Interest Transition, Scene 5.

For evaluation the moving area of interest sequence was viewed on a screen which produced a display 46 inches in height. A viewing distance of 40 inches provided the 60-degree vertical field of view for the scene.

When the gaze was fixed on the medium range cylinder, the transition from an 8-sided version to a 4-sided version was detectable. When the gaze was fixed on the close range bus, the transition to the version with windows was noted. However, when the gaze tracked the cross designating the center of the area of interest, these transitions were not noticed.

The effect of moving area of interest on the runway stripes was apparent even when the cross was closely tracked. The large areas of white dropping off to the black runway do not require sharp vision to detect. When a feature such as this is so close, perhaps a fall-off version with a single stripe for the centerline would save edges, and reduce the discernability of the transition effect. It is probable that there are some cases -- this may be one -- where the full detail model must be used even outside the area of interest. Additional experimentation is needed.

In summary, these preliminary results show that there are situations -- the bus and the cylinder -- where the transition algorithm applied produces fully satisfactory results. They further show that it can be misapplied, and hence that modeling and selection of levels of detail must be designed to prevent this.

3.4 OPERATIONAL IMPLEMENTATION

It would be possible to configure real-time hardware to produce scenes with the level-of-detail transition based on area of interest, using the same technique that was used to produce the evaluation scenes. This would come close to doubling the system cost. Except for the display system, most of the CIG system would have to be duplicated, with hardware to produce the composite scene from the individual scene added. Even though the edge capacity might be reduced, it does not seem possible that this could result in a net saving.

In contrast to the situation discussed in Section 2 with gradual level-of-detail transition, no place was found in the sequence of image generation functions where any simpler processing would achieve the same results. It is in the very nature of what must be done, that very complex, high-speed pixel-rate processing would be required. This will inevitably be expensive, and in any specific case, the effectiveness of the resulting system must be compared with that of an alternative system in which additional edge capacity is provided for the same total cost.

An alternate approach to implementing area-of-interest oriented LOD was devised after the above portion of the study. It is based on the assumption that the system incorporates the gradual transition applicable to an entire level-of-detail entity, be this a model, an object, or a face. In the standard application of this type of transition, a level-of-detail parameter will be computed using criteria discussed in Section 4 of this report. As this parameter varies, the computation of the scene will change from a pure version of one level of detail, through a transition which blends two levels, and finally to a pure version of a second level of detail.

Applying this to area of interest will involve using the view window position of each entity, relative to the location of the area of interest, as a very significant input in determining the level-of-detail parameter. Now if we consider an entity 180° from the view direction, and then smoothly change view direction until the area of interest is centered at the entity, it will smoothly change through several levels of detail, from very low to very high, in a very satisfactory manner.

If the view is shifted abruptly, it may be desirable to introduce a time lag factor in the level-of-detail parameter variation, so this cannot cause abrupt, pop-in types of level-of-detail changes. Due to the fact that this concept was a last-minute development in this contract, it was not possible to produce evaluation scenes applying it.

3.5 CONCLUSION

Unless some breakthrough leads to a relatively inexpensive approach to hardware implementation of gradual spatial transition, gradual spatial transition does not appear to be a viable approach to improved CIG cost effectiveness. However, where gradual transition of an object or model, based on a computed level-of-detail parameter, is part of a system, then using area of interest as a factor in computing this parameter has the potential of providing the major efficiency gains possible with area-of-interest detail, with practically no cost impact.

SECTION 4

LEVEL-OF-DETAIL ALGORITHM

4.1 INTRODUCTION

One of the areas of study specified for this program is that of the LOD control algorithms. As used here LOD may be defined as the variation of some characteristics of an object or model as a function of its distance from the viewer. The characteristic variation may be in the amount of detail, in the coloration, in the size, or in any other visible characteristic. The overall objective is to keep objects or models from being seen while they are too small and to gradually introduce them in more detail and in full color. This helps to keep the edge and face loading of the system to a minimum. As usually implemented, LOD is a step-type function, a factor which raises some problems.

The discussion of LOD which follows is based on a historical approach showing how the LOD concept has changed, leading to recommendations for changes in future systems.

4.2 ORIGINAL APPROACH

The CIG system built for the U.S. Navy as an addition to the 2F90 Flight Trainer for TA4J aircraft used a very simple form of LOD control. There were four steps (including complete removal) in the LOD. The slant ranges at which the LOD changes were made from the highest LOD to the second, from the second LOD to the third, and the removal of the object, were specified for each model. This approach worked well for three dimensional (3D) objects but poorly for two dimensional (2D) surface objects, particularly when viewed at low approach angles. This system did not incorporate any form of overload control.

4.3 ADVANCED SIMULATOR FOR PILOT TRAINING (ASPT)

The ASPT system is an experimental aircraft flight training simulator built for the Air Force Human Resources Laboratory at Williams AFB. General Electric supplied the CIG portion of this system.

The ASPT system modified the original approach by relieving the modeler of the responsibility of determining the transition ranges; instead they were determined automatically based on the size of the model.

The basic concept of the ASPT approach is related to the size of an element in a digitally generated raster scan display. Each raster line has N number of generated elements; in the case of ASPT, N = 1024. Thus, it was reasoned that no model should be shown which did not occupy the space of at least one element on the display. The change to the next LOD would be made when the model occupied several elements, etc. The transition point would be determined by an algorithm which calculated the transition range based on the size of the model and the size of a display element.

In ASPT, the radius, called the critical dimension, of a sphere which would completely surround the model was calculated by the computer off line, for use in size comparison tests. For 3D models, this was used directly. ASPT used three LODs and the number of elements to which the comparison was made was one for LOD 3, 2^2 or four for LOD 2, and 2^3 or eight for LOD 1.

In mathematical terms, r_c, the critical dimension or radius of the sphere is given by

$$r_c = \text{maximum value of } (X^2+Y^2+Z^2)^{\frac{1}{2}} \qquad (1)$$

where X, Y, Z define the model around its centroid.

The relationship between the critical dimension and the slant range to the centroid of the model is shown in Figure 39, in three-dimensional space:

$$\text{Tan } A = \frac{r_c}{R_s} \text{ ; where } R_s = \text{slant range} \qquad (2)$$

$$A = \text{angle subtended by } r_c$$

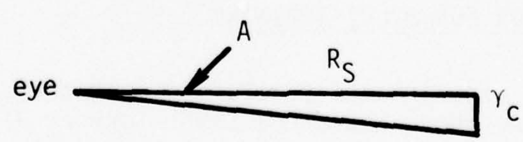

FIGURE 39

LEVEL-OF-DETAIL PARAMETERS - THREE-DIMENSIONAL SPACE

The view window parameters are shown in Figure 40,

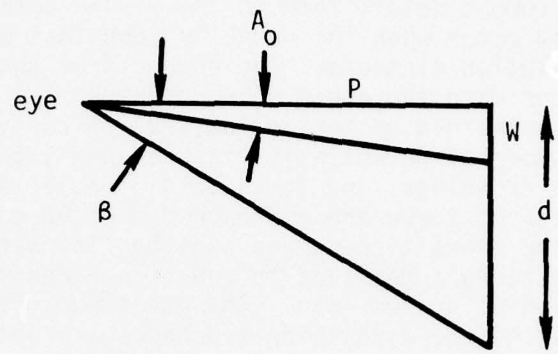

FIGURE 40

LEVEL-OF-DETAIL PARAMETERS - VIEW WINDOW SPACE

where w = The width of one resolution element

d = half width of the screen

J_m = display elements per raster line

A_o = angle subtended by one element

P = distance from viewpoint to screen

β = angle subtended by half screen

Then

$$w = 2d/J_m \tag{3}$$

$$\tan A_o = \frac{w}{P} = \frac{2d}{J_m P} \tag{4}$$

When $A = A_o$ (equation 2) then the slant range is such that the critical dimension occupies one resolution element.

$$R_s' = \frac{r_c}{\tan A_o} \qquad \text{slant range at which the critical dimension equals one resolution element.} \tag{5}$$

Slant range R_s' is then defined as the range at which the model enters of leaves the scene in its lowest detail form.

The change from the lowest detail form to the middle detail form (or vice versa) would occur when the range is such that A is the angle subtending four resolution elements. The change from the middle-detail model form would occur when the angle subtends eight resolution elements. Overload control was obtained by monitoring several counters giving the status of the number of potentially visible edges, the edges input to Frame 2, the edge crossings, and the number of objects in the scene. When the system limits of these are approached the LOD constants are adjusted to reduce the transition ranges and thus the system load. This was done by inserting a constant in equation 5 and varying this constant as a function of system load. The exact equations are not important in the rest of the discussion and hence are not given.

Provision was made to permit the calculated critical dimension of 3D models.to be modified to a selected value if the transition ranges selected by the calculated value gave unsatisfactory results.

For 2D models, a correction was made to the critical dimension based on the vertical-viewing angle, or angle of observation. This assumed that all 2D models were used for surface objects such as fields, roads, rivers, etc.; a very good assumption. When seen from close to the ground, such a surface object presented a very narrow view. As the altitude of the viewpoint increased, the size of the object as viewed increased. Thus the range determination algorithm was modified to increase the range at which a 2D model was viewed as a function of the height of the viewpoint above ground.

Figure 41 shows the relations involved in LOD selection for surface features, where:

$$d = \text{effective projected length of } r_c$$

$$= r_c \sin\beta$$

$$\tan A = \frac{d}{R_s} \qquad (6)$$

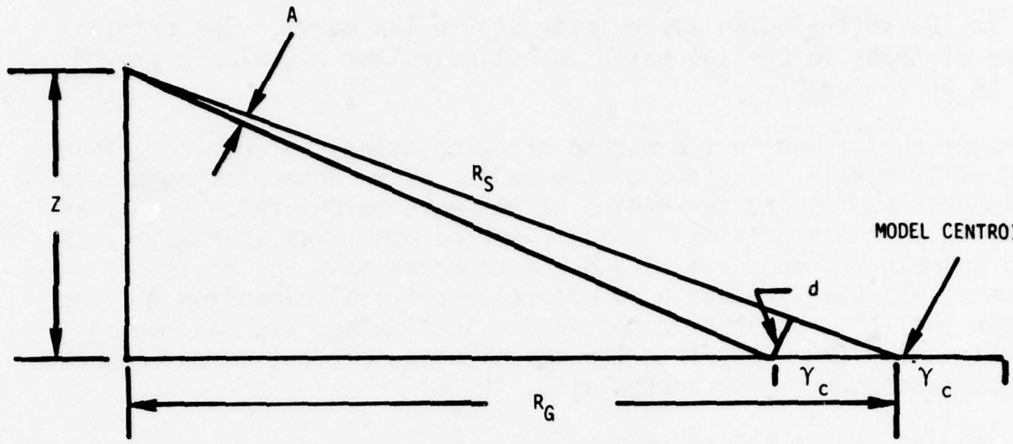

FIGURE 41
LEVEL-OF-DETAIL PARAMETERS FOR SURFACE FEATURES

$$\sin\beta = \frac{Z}{R_s} \tag{7}$$

Hence $$\tan A = \frac{r_c \cdot \frac{Z}{R_s}}{R_s} = \frac{r_c Z}{R_s^2} \tag{8}$$

or $$R_s^2 = \frac{r_c Z}{\tan A} \tag{9}$$

The rules for changing LOD are the same as for the 3D model case.

4.4 2B35 AND RELATED SYSTEMS

The 2B35 CIG system was designed to work with the TA4J aircraft. Since it was designed after the ASPT, its design incorporated improvements suggested by that program. One was to increase the number of LOD steps, and this was done, going to eight steps. Another was to introduce the concept of K_{LOD}, the LOD constant. This was only a way of specifying the size of a display element in a form that was more conveniently varied for systems which have different resolutions.

A more significant change was to make the referenced number of elements defining the transition between LODs a design selectable value stored in a programmable read only memory. The values selected began at 3 and

went to 150 following an approximate sqaure law curve. The original choice of these values was based on estimates but experience proved them to be reasonable.

The major change was in the method of calculating the critical dimensions of 2D models. Instead of the radius of an encompassing circle, the longest radius and the radius at 90° were calculated. No way of modifying them was provided. Then when the model was approached, the angle between the long radius and the approach path, or angle of subtense, was used to obtain an effective critical dimension varying between the long and short dimensions. This method was adopted in order to delay the entry into the visual scene of long narrow objects when approached form the narrow side.

Thus, for 3D models, equation 2 became

$$\tan A = \tan N_e A_o \approx N_e \tan A_o = \frac{r_c}{R_s}$$

$$N_e = \frac{r_c}{\tan A_o R_s}$$

$$N_e = K_{LOD} \frac{r_c}{R_s} \qquad (11)$$

where N_e = number of resolution elements

K_{LOD} = level-of-detail constant

The number of elements for transition between LOD steps was selected to follow a square law of the form $N_e \approx K \ (\text{LODStep})^2$

The modifications for the 2D LOD algorithm were more extensive. Consider Figure 42:

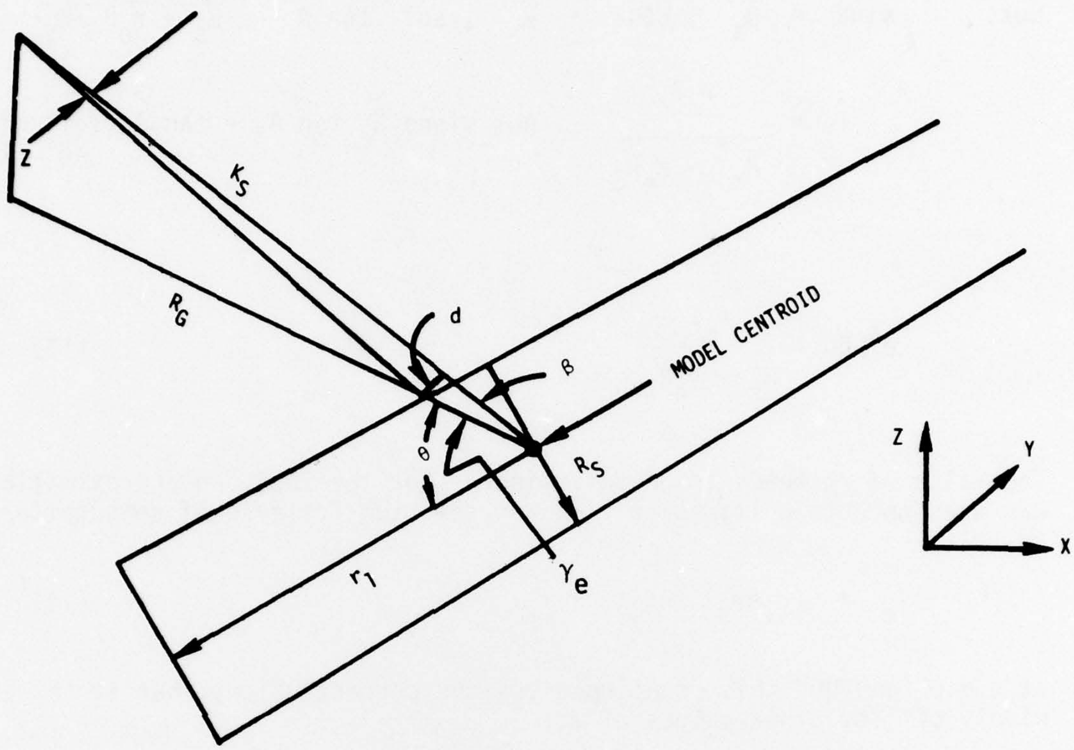

FIGURE 42

MODIFIED SURFACE FEATURE LEVEL-OF-DETAIL PARAMETERS

r_e = effective radius

r_s = short radius

r_1 = long radius

θ = angle of subtense

β = angle of observation

$$\tan A = \frac{d}{R_s - r_e \cos\beta} = \frac{r_e \sin}{R_s - r_e \cos\beta} \qquad (12)$$

But: $\sin\beta = \frac{Z}{R_s}$, $\cos\beta = \frac{R_G}{R_s}$, so: $\tan A = \frac{r_e Z/R_s}{R_s - r_e R_G/R_s}$

$$= \frac{r_e Z}{R_s^2 - r_e R_G}$$

. But since $N_e \tan A_o = \tan A$ (following eq. 11)

$$N_e K_{LOD} \quad \frac{r_e Z}{R_s^2 - r_e R_g} \tag{13}$$

The value of r_e needs to be determined. For the 2B35, an approximation was used to obtain its value. It was selected for ease of computation.

$$r_e \;+\; (r_\ell - r_s)\,|\cos|\,\theta \;+\; r_s \tag{14}$$

at $\theta = 0°$ and $90°$ this equation gives the correct values, but it is widely off for other values of θ.

A more correct value for r_e, but more difficult to calculate, would be obtained using the polar form of the equation for an ellipse. This is

$$r_e^2 = \frac{r_\ell^2 \; r_s^2}{r_s^2 \cos^2\theta + r_\ell^2 \sin^2\theta} \tag{15}$$

which can be reformulated into several forms.

The transition between LODs for 2D models was accomplished in the same manner as for 3D models. Also, r_c could be fine-tuned for 3D models by permitting the modeler to enter a value other than the calculated value. No such provision was made to r_e for 2D models because of the more complex method of calculating.

These systems did not incorporate any form of overload control except for one system which was specially modified. In this system, the potential number of faces, the number of active models, the number of point light faces, the number of edges, and the number of point lights were monitored. When any exceeded a specified maximum value, then the K_{LOD}

constant was decremented a fixed amount each frame time until the overload stopped. There is also a table of minimum values which is used to increment K_{LOD} when the monitored values fall below the minimum values.

One other new feature was incorporated in these systems. This is face removal due to visibility. When the fading of a face due to low visibility reaches a point where the face is almost completely faded (approximately 98%), the face is dropped from the visual scene. This reduced the possibility of system overload and allowed the remaining visible models to be seen in a higher LOD.

4.5 AVIATION WIDE ANGLE VISUAL SYSTEM (AWAVS)

This CIG system was built for the Naval Training Equipment Center as part of their overall development system. Again experience suggested some improvements in the LOD techniques as compared to the 2B35 type systems.

The first change was to incorporate a mixture of face and model determined LOD rather than the all model determined as used in past systems. All 2D LOD is based on face size using the same algorithm as before except that r_e is determined from face rather than model data. The 3D LOD is based on model size using the same algorithm as before. But in addition, each face in the 3D algorithm is subject to the operation of the 2D algorithm. This is done on the basis that the transitions would be more effective is based on face size rather than model size. This does pose a constraint on the modeler to make sure that the removal of a face does not leave gaps in a model.

As mentioned earlier, there had been no way of fine-tuning the critical dimension on 2D models. Its size can now be changed, as can the direction of the major axis. Another aid for fine tuning was incorporated by allowing the modeler to select between two N_e vs LOD curves, the first being the same as that used for the 2B35 while the second uses smaller values for N_e.

A blending control is also incorporated, whereby the colors of faces can be varied between their normal color and the color of the area behind them. The amount of this blending is a function of the size of the face and the range from the viewpoint to the face. It reduces the pop-in or pop-out effect when objects are introduced or removed from a scene without requiring objects to be maintained in the scene at the long ranges.

4.6 FUTURE IMPROVEMENTS

The experience gained on designing the systems which have been described and in operating a 2B35-type system in the engineering laboratory has increased the awareness of needed improvements in the LOD algorithms. The AWAVS CIG system has been completed recently so that only limited visual data bases have been viewed on it, hence the effectiveness of the changes incorporated in it are unknown. The laboratory 2B35 system has provided a wealth of information, largely because it has been used to develop and generate visual data bases for many purposes. This has included aircraft takeoff and landing, aerial refueling, aircraft carrier landing, helicopter, low flying cargo aircraft, army tank battles, and weapons delivery. Thus, the following discussion is based largely on this experience.

The specification for this study required that a number of parameters be considered as criteria in the LOD selection algorithm. These are slant range, altitude, attitude, angle of observation, and angle of subtense. The last two parameters need to be defined. The angle of observation is the vertical angle that lies between the line-of-sight and the ground plane. It is equivalent to the glideslope angle for landing aircraft. The angle of subtense is the horizontal angle between the centerline of a face or a model and the vertical plane through the line-of-sight.

All of these parameters, except attitude, have been incorporated in the algorithms previously discussed. In addition, the parameters of size (face, object, or model), display resolution, overload, and visibility have been incorporated. As a result of experience it is suggested that another factor be incorporated, that of cue requirement. The overload prevention technique varies K_{LOD} and thus eliminates visible items based on size, but in doing so the relative importance of the visible items as visual cues to the pilot is ignored. Thus, consideration must be given to two additions to the parameters already incorporated in the LOD selection algorithms: attitude and cue importance.

The attitude of an aircraft is important because it affects the relative amounts of the ground terrain and sky which are included in the visual scene. Obviously, an attitude which shows all ground terrain will have many more scenic faces and models included than one which shows only clear sky. This suggests that the LOD selection algorithms should be operated normally unless overload occurs. By normally it is meant that the factors such as size, slant range, etc. which are already included in the algorithms should be the main selection criteria. Therefore, no change to the algorithms to include attitude is recommended.

Since cue importance is a new concept in LOD selection, no techniques exist for utilizing it. Thus, the following approach is suggested. During the preparation of the visual data base, the modeler should indicate which faces or models are of critical importance and should be given favorable retention priority under overload conditions. Unless these indications are made, a face or model will be given normal treatment. This indication will be utilized by retaining a fixed K_{LOD} for those faces and models of importance and varying K_{LOD}, as previously discussed, for the normal faces or models.

The altitude factor which is included in the 2D LOD selection algorithm is intended to indicate the projected size of faces rather than the other two effects of altitude. The first of the two effects is concerned with slant range. As the altitude increases, the slant range to the terrain and models on the terrain increases. The slant range parameter in the LOD selection algorithms will give the correct results for this effect, a linear change in LOD. The other effect is that of increased area coverage. As the altitude increases, the terrain area viewed for a given attitude increases approximately as the square of the altitude. Thus, as altitude increases, the major problem is system capacity overload which is controlled by the overload control feature. This factor, plus the attitude discussion, explains why so much emphasis is given to overload control. This is particularly true when it is desired to utilize the system capacity to the fullest extent under all conditions.

4.7 FINAL ALGORITHMS

In this section the recommended LOD selection algorithms are summarized. For 3D models, either on or above the terrain, the suggested form is

$$N_e = K_{LOD} \frac{r_c}{R_s} f(v) \qquad (16)$$

where

N_e = number of display elements

K_{LOD} = level of detail constant

R_s = slant range

r_c = maximum value of critical radius

$f(v)$ = function of visibility-removes model when fading due to low visibility is 98%

A_o = angle of one resolution element from viewpoint to viewplane

For 2D models or faces the suggested form is

$$N_e = K_{LOD} \frac{r_{eH}}{R_s^2 - r_e R_g} f(v) \tag{17}$$

where

H = relative altitude

R_s = slant range

R_g = ground range (flat earth)

r_e = effective radius

and

$$r_e^2 = \frac{r_\ell^2 r_s^2}{r_s^2 \cos^2 \theta + r_\ell^2 \sin^2 \theta}$$

r_s = short radius

r_l = long radius

θ = angle between r_e and r_l

K_{LOD} is adjusted for overload except for models defined as of cue importance. This is done by monitoring all critical system capacity factors (those which cause visible scenic effects when the design value is exceeded) and decrementing K_{LOD} when the capacity factors fall below other specified values.

The table of N_e vs LOD steps should be designed to approximate a square law, i.e.

$$N_e \approx K(\text{LOD STEP})^2 \tag{18}$$

4.8 DISCUSSION OF OTHER FACTORS

A number of factors affecting the utlization of these algorithms are discussed in this section.

4.8.1 DESIGN OF MODELS

It is not always necessary that there be a different design for a given model in each LOD step. Quite often the same design can be used for several LOD steps, sometimes even being the same for all LOD steps. The modeler must use judgement. In designing the models for different LOD steps, two different approaches or a combination of them can be taken. In the first, the amount of detail in a model is reduced at each coarser LOD step. For example on a house, the windows, doors, etc. would be shown in high detail models but removed in lower-detail models. The other approach is to redesign the model for each LOD step. For example, in an aircraft the fuselage can be made simpler by having fewer faces in the cross section. This approach can result in noticeable variation in the outline of the model between LODs and should be used with care.

This brings us the whole subject of blending during the transition between LOD steps. The techniques for this are discussed in Section 2 of this report. Blending is important not only to decrease the noticeability of the elimination of detail and the change in outline but for two other major reasons. First, it permits an earlier transition between models of different detail, thus reducing the system load earlier. Second, it masks the variable transitions which result from the operation of the overload control. As a general guide it is desirable to design the models for each LOD step so that the ratio of edges between them is 2 to 1. This is consistent with using the recommended square law for the relationship of the number of visual elements in LOD steps.

4.8.2 ALGORITHM VALUES

It would be desirable if, in addition to the LOD selection algorithm, the recommended constants for the various fixed terms could also be given. This is difficult because of the wide range of characteristics in CIG systems. An example can be given. Suppose that the system has a display of 40° horizontal field-of-view with 1024 elements per horizontal line. Then (see Table 3).

$$A_\circ = \frac{FOV}{N_e} = \frac{40}{1024} = 0.039^\circ$$

$$\text{and} \quad K_{LOD} = \frac{1}{\tan A_\circ} = \frac{1}{\tan 0.039} = 1467$$

TABLE 3. N_e FOR LEVEL OF DETAIL STEPS

LOD STEP	N_e(Actual)	N_e(approximate)
8	96	96
7	73.5	74
6	54	54
5	37.5	38
4	24	24
3	13.5	14
2	6	6
1	1.5	2

Where N_e (Actual) = 1.5 (LOD STEP)^2

For overload control Table 4 is representative:

TABLE 4. OVERLOAD CONTROL CONSTANTS

Parameter	System Capacity	Begin KLOD Decrement	Begin KLOD Increment
Edges	8192	8000	6000
Point Lights	4096	4000	3000
Faces	4096	4000	2700
Edge Crossings/line	1024	1000	700

Decrement step = 10
Increment step = 10

All of the other values in the algorithm depend on the viewpoint and visual data base, hence no fixed values can be given.

All of the fixed values given can and should be modified to fit the particular mission to be performed and the particular data base. These values can easily be changed by software control. The best values to be used can only be found after tests are made.

4.8.3 DATA BASE MEMORY

The only effect of the use of LOD on the data base memory is that it will be required to store each model in all of its LOD steps. If every model uses all levels of detail and the number of edges between them varies as a factor of two as previously discussed, then the size of the data base memory would have to be twice the size of a memory storing a data base without LOD. This is shown in Table 5.

TABLE 5

LEVEL-OF-DETAIL MEMORY IMPACT

LOD Step	No. of Edges
8	1,000
7	500
6	250
5	125
4	62
3	31
2	15
1	7
	1,990 edges

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 GRADUAL LEVEL-OF-DETAIL TRANSITION

The evaluation results fully verify the value of this technique. A LOD transition, which is extremely noticeable and distracting when it takes place abruptly, becomes hardly noticeable when done gradually.

Implementation of gradual transition by using translucent faces not only is a hardware-feasible approach to this goal, but also results in a system with the other advantages of translucent face capability. It is therefore recommended that future high-performance CIG systems incorporate translucent faces and gradual LOD transition.

5.2 AREA-OF-INTEREST LEVEL OF DETAIL

The results of implementing area-of-interest LOD with a gradual spatial transition between levels appeared to be quite satisfactory. However, no approach to implementation on an operational system without inordinate expense was devised.

Area-of-interest LOD can be implemented without the spatial transition, by using a system with gradual LOD transition and employing the relationship between feature location and area of interest as a level-of-detail parameter. This approach will have a very minor cost impact, and it is recommended that this be done. There are a number of unknown factors in how best to vary parameters as the criteria vary. This part of the design should retain a high degree of flexibility even on operational systems, not only to help in resolving the unknown areas, but to allow for different control formulas for different scenes and missions.

5.3 LEVEL-OF-DETAIL ALGORITHM

The LOD algorithm should provide the modeler and the test conductor with a variety of criteria on which to base selection, and with a high degree of flexibility in the use of these factors. This is an area in which significant improvements in results can be obtained with very minor cost impact. It is believed that the algorithms suggested in Section 4.7 will provide improved performance as compared with past and present systems, and it is recommended that future systems include capability to implement these algorithms.

SECTION 6

TENTATIVE SPECIFICATION

6.1 DETAIL CONTROL PARAMETER

For each scene and for each entity in the environment subject to LOD variation, the system shall compute a detail control parameter, N_e. This computation shall as a minimum implement the algorithm of section 4.7 of this report, although it may include any other factors the contractor feels may be desirable. The implementation shall have sufficient flexibility that any subset of the factors may be used as desired.

N_e as computed above shall be subject to modification based on the relationship on the viewing surface between the location of the entity and the center of the area of interest.

6.2 LEVEL SELECTION

There shall be a one-to-one relationship between the value of N_e and the selected level of detail. The exact relationship shall be stored as a table in memory, for flexibility. The nature of the relationship shall be as illustrated in the following:

$0 < N_e < 1.5$	Use Level 1
$1.5 < N_e < 3$	Combination of Level 1 and Level 2
$3 < N_e < 6$	Use Level 2
$6 < N_e < 9$	Combination of Level 2 and Level 3

etc.

6.3 IMAGE GENERATION

When the control parameter designates a specific level of detail for an entity, that level shall be computed and displayed. When the parameter calls for a combination (e.g., $N_e = 6.75$, compute .75 Level 2 + .25 Level 3), then each pixel shall have computed for each color component the value which would result if scenes were generated separately using the two levels and the computed values of video were then combined with the indicated weighting.

6.4 COMMENT

The above is a very generally worded specification. It should be applicable to any system and completely nonconstraining in regard to implementation details. Nevertheless, a system which complies with this specification will meet the performance requirements for gradual transition and area-of-interest LOD as recommended in this study and will benefit from the improved level-of-detail selection algorithm.

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